THE UNIVERSITY OF ALBERTA

EFFECTS OF PREVIOUSLY APPLIED PHOSPHORUS ON BARLEY GROWN ON ALBERTA SOILS

by

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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

SPRING, 1974

ABSTRACT

Six Alberta soils, which had varying rates of fertilizer phosphorus applied to them for four or five years, were investigated to determine if an accumulation of phosphorus occurred with time and to see if crops could utilize this "residual" phosphorus. Two years after fertilization was terminated in the field, bulk soil samples were taken for laboratory and greenhouse studies. Total phosphorus was determined prior to the first greenhouse crop. Extractable phosphorus analyses were also done before the first greenhouse crop, as well as after each greenhouse crop. Dry matter yields of each of the four greenhouse crops were taken and phosphorus content was determined on the plant material.

It was found that for all sites studied, extractable phosphorus in the soil increased as a result of fertilizer phosphorus applications over a number of years. This increase varied with the amount of phosphorus applied as well as the type of soil. It was also shown that the "residual" phosphorus which had been built up over time could be utilized by plants. Extractable phosphorus in the soil and phosphorus in the plant showed a steady decrease with cropping.

It was concluded that extractable phosphorus will be increased in most soils when fertilizer phosphorus is applied for a number of years at rates in excess of crop removal. The extent of extractable phosphorus built up depends, to a large extent, upon the amount of phosphorus the soil can "fix" or render unavailable to plants. Soils which have high "fixing" capacities show small increases in extractable phosphorus over time and require somewhat higher rates of fertilizer phosphorus than would low phosphorus "fixing" soils.

ACKNOWLEDGEMENTS

Sincere appreciation is expressed to Dr. J. A. Robertson for his valuable guidance and encouragement throughout the course of this study. His criticism and assistance in the preparation of the manuscript is sincerely appreciated.

Appreciation is extended to Dr. G. R. Webster and Dr. W. G. Corns for their suggestions for improving the manuscript.

Thanks are extended to Mr. W. Oborn, Mr. J. Konwicki and Mr. B. Fielhaber for their assistance throughout the course of this study.

Special thanks to Mrs. Rita Alexander for her careful typing of the manuscript and to Dr. T. G. Alexander for his advice and assistance on many aspects of the research.

I would like to give very special thanks to my parents for their sacrifice and encouragement throughout the course of my studies.

And finally, to my fiancee, Lynda, I express my deepest gratitude for her understanding and encouragement.

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I INTRODUCTION

While phosphorus is acknowledged as being very important in plant nutrition, relatively small amounts (much less than nitrogen and potassium) are taken up by plants. However, due to the low efficiency of phosphorus fertilizer, the amount of phosphorus applied is similar to, and often exceeds that of nitrogen fertilizers. One of the most important reasons for this low efficiency is the soil's ability to "fix" the fertilizer phosphorus into a relatively unavailable form which plants are unable to utilize. The degree to which a soil can accomplish this depends upon a number of factors including pH, type of clay present, organic matter content, soil moisture and temperature.

A great deal of work has been done on the subject of phosphorus. Due to its lack of mobility, phosphorus is generally never lost from the soil in any appreciable amounts and should therefore be increased in the soil when fertilizer phosphorus is applied at rates exceeding crop removal. Theoretically this "residual phosphorus" should increase over time to such an extent that eventually soils would need only "maintenance" amounts of fertilizer each year. However, the fate of phosphorus in the soil is extremely complex and, as mentioned before, is subject to large numbers of variations which make it difficult to predict how fertilizer phosphorus will react when introduced into a particular soil.

Much of the work concerning availability of residual phosphorus has been carried out in the United States and relatively little work has been done in Western Canada and especially Alberta. Therefore, this project was initiated to study whether or not extractable phos-

phorus was increased in the soil after a number of years of phosphorus fertilization and whether crops were able to utilize any of this "residual" phosphorus.

II LITERATURE REVIEW

The importance of phosphorus in plant nutrition is attributed to its effect on maturation of cereals, root growth, strength of straw in cereal crops, disease resistance, flowering and fruiting, and general crop quality. Biochemically, it is recognized as a constituent of nucleic acid, phytin and phospholipids (Tisdale and Nelson). A lack of this element may prevent other nutrients from being taken up by plants. The interrelationship between nitrogen and phosphorus has long been known, and prior to extensive use of commercial fertilizers, most of the soil nitrogen was indirectly dependent upon the supply of phosphorus, due to the influence of phosphorus on legume growth (Buckman and Brady 1968).

Although phosphorus is very important to crop production, plant requirements and therefore crop removal is lower than for nitrogen and potassium, often being only one third or one quarter that of the other two elements (Buckman and Brady 1968). However, the amount of fertilizer phosphorus applied is frequently half that of fertilizer nitrogen. For example, the total tonnage of phosphorus (P) sold is more than 45 percent of any other fertilizer nutrient sold in the United States (Buckman and Brady 1968). This trend is probably very similar in Canada and is certainly true in the provinces of Alberta, Saskatchewan and Manitoba (Robertson 1969). It becomes apparent that if large quantities of phosphorus relative to nitrogen must be added to insure good crop growth, then either the recovery of the added phosphorus by the plants is low or a large percentage of it is lost from the soil by other means.

Studies have shown that only a fraction of fertilizer phosphorus

added to the soil is utilized by plants (Campbell 1965, Leamer 1963, Soper and Racz 1967). When 26 pounds per acre of phosphorus was added to the soil both Campbell and Leamer found that only 17 percent was utilized by the crop in the first year. After six years, less than 50 percent was utilized by the crops. Soper and Racz state that 20 to 30 percent of the added phosphorus is utilized by the plant in the first year.

Several ways by which phosphorus might be lost from the soil can be suggested. Leaching of soil phosphorus may be important in coarse-textured soils, or soils high in organic matter (Sutton and Larsen 1963). However, because of the very limited mobility of phosphorus compounds, very little downward movement of phosphorus is thought to occur in most soils (Tisdale and Nelson 1967, Buckman and Brady 1968, Maclean A. A. 1964, and Rich et al 1948). Erosion could also be a very serious problem in areas of high rainfall or high wind when accompanied by poor soil management. Where these factors exist, erosion could be very serious because of the tendency to remove the finest soil particles highest in nutrients, including phosphorus. Although the problem is undoubtedly serious in some areas, it could not be considered to be a factor when discussing the universal inefficiency of phosphorus fertilizer.

Another recently proposed mechanism of phosphorus loss is through reduction of phosphorus to phosphene, and hence, loss in the gaseous form (Tsuboto 1959). Very little research has been conducted in this area, but it would be surprising if loss by this mechanism was normally significant. More work is obviously needed on this subject. We can tentatively conclude therefore, that not much phosphorus is

lost from the soil by leaching, erosion or in gaseous form.

If the fertilizer phosphorus cannot be recovered readily by plants and is not being lost from the soil, then it must be present in the soil in some "fixed" form which is less available to plants. This phosphorus which is left in the soil is termed residual phosphorus and is present in various forms. The factors which affect the fixation of available phosphorus are therefore of some importance. Several reactions of the applied phosphorus with the soil have been proposed.

A. Factors Affecting Phosphate Fixation

The pH of the soil is indirectly an important factor in the fixation of phosphorus. Some researchers (Benne et al 1936, Teakler 1928, Wiley and Gordon 1923 as cited by Allison 1943) report that the fixation of phosphates is mainly due to calcium when the pH is greater than 6.0. (Chang and Chu 1961), however, demonstrated that in soils of pH 5.3 - 7.5, added soluble phosphorus was fixed mainly by aluminum followed by iron and calcium. Other workers, too, have proposed that aluminum appears to be the dominant factor in phosphorus retention (Saini and Maclean 1965, Bromfield 1964, and Williams et al 1958). Wild (1950), on the other hand, showed that only at pH levels below 4.5 are any appreciable amounts of iron and aluminum phosphates formed. There are a large number of unknown variables in soils which make it virtually impossible to accurately predict at what pH value specific reactions stop and different reactions take over.

Rathji (1960) proposed that phosphorus equilibria in soils could be represented by the following reaction:

$$\text{Ca phosphate} + \begin{matrix}\text{Al}\\ \text{Fe}\end{matrix}\Big\}\ \text{hydroxide} \rightleftarrows \begin{matrix}\text{Al}\\ \text{Fe}\end{matrix}\Big\}\ \text{"hydroxide phosphate"} + \text{Ca hydroxide}$$

A shift to the left occurs as a result of an alkaline reaction and to the right by an acid reaction. In effect, Rathji refuses to attach a specific pH range where phosphate compounds have greater or lesser solubility. His proposal appears to take into account the wide range of variables which affect both pH and phosphate solubility; variables which apparently were not taken into account judging from the contradictory results obtained by the workers in the previous paragraph. If the specific pH values assigned by these workers are ignored, it becomes apparent that there is little disagreement among the results obtained. Other workers also appear to be in agreement with Rathji's proposal (Sacki and Okamoto 1960, Bromfield 1965, Hsu 1964, and MacKenzie 1962).

The pH of the soil solution has also been found to be a factor with regard to plant uptake of phosphorus. Maclean and Cook (1955) have shown that the best uptake of native phosphorus by alfalfa occurred at a pH of 7.5. They found that liming the soil to 6.5 or 7.0 gave maximum yields of alfalfa on soils where phosphorus was added. Others have found that liming of acid soils tends to increase the availability of phosphorus (Beater 1945, Dunn 1943, MacIntire and Hatcher 1942, and Salter and Barnes 1935). In contrast, Neller (1953) found that increasing the pH of acid soils by liming did not increase the uptake of phosphorus by oats and millet. The opposite results obtained by Maclean and Cook, and Neller may be partly explained by crop species as it is likely that types of crops play an important role in determining phosphorus uptake.

There appears to be a close relationship between clay percentage and phosphate retention (Wild 1950). Olsen and Watanabe (in Campbell 1956) stated that to attain a given phosphate concentration in the soil solution, 3.9 times as much phosphorus had to be added to a clay soil as for a fine sandy loam. They further stated that for every 10 percent increase in the clay content, an additional 22 pounds of phosphorus was required to obtain an equal recovery by plants. Soper and Racz (1967) suggest that the phosphate ions may replace OH^- ions at the edge of clay lattices, OH^- ions associated with Al^{+++} ions at the crystal edges, or other ions held on positively charged sites of clay particles. The type of clay present, as well as the amount, appears to be of some importance in this respect (De 1960, Stout as cited by Allison 1943, Allison 1943, Kanwar 1962, and Alexander 1967). However, other workers have found little relationship between phosphorus fixation and clay content (Franklin et al, 1960, Williams et al, 1958 and Saini et al 1965). Saini and Maclean (1965) are convinced that the role which has been attributed to clay is due to active aluminum, and possibly iron, which were associated with it. If so, the clay is therefore relegated to an indirect, rather than direct, role in phosphorus fixation.

The organic matter or humus content of the soil is effective in decreasing the amount of fixation of phosphorus. Some workers have shown increased fixation with the removal of humus from the soil (De 1961, Dunn 1943). De (1961) believes that the humus partially saturates the secondary valences of the mineral lattices and thereby cements the soil particles together. The resulting reduction in surface area causes a reduction in phosphorus fixation. Many

organic substances commonly found in soils are very effective in preventing the precipitation of phosphate by iron and aluminum between pH values of 3.0 to 9.0 (Struthers and Sieling 1950, and Swensen 1949). Others state that various fixed phosphate substances are readily broken down by the action of organic substances thereby releasing phosphorus for plant uptake (Mattson as cited by Maas and Bentley 1946). Saini and Maclean (1965), however, have suggested that organic matter may increase phosphorus retention through a direct combination of organic matter and phosphorus. They go on to say, however, that a more plausible explanation for phosphorus retention by organic matter is aluminum associated with the organic matter and not by the organic matter itself.

Microbial activity may also result in immobilization of soil phosphorus. Alexander (1961) stated that phosphorus may be both mineralized and immobilized, depending upon the percentage of phosphorus in the plant residues undergoing decay and the nutrient requirements of the responsible population. Consequently, in the decomposition of substrates poor in phosphorus, a portion of the available nutrient supply may be immobilized from the surroundings.

Several other factors have been implicated in phosphorus retention. The percentage of moisture in the soil may affect the rate of transformation of the more soluble Al-phosphates to the relatively insoluble Fe-phosphates (Chang and Chu 1961). The higher the moisture content, the faster is the transformation process. Other workers have shown different fixation capacities of the soil depending on the temperature (Muljade 1966). The addition of some salts, especially sodium salts, may increase the solubility of calcium

phosphate (Wild 1950, Tobia et al 1964, and Soper and Racz 1967).

Soper and Racz have shown that the inorganic phosphorus compounds which form in the soil, determine to a large degree, the availability of the applied phosphorus. In the provinces of Western Canada, the main inorganic phosphorus compounds formed are of calcium and magnesium. Compounds such as $CaHPO_4 \cdot 2H_2O$ and $MgHPO_4 \cdot 3H_2O$ are relatively soluble and could therefore provide relatively large amounts of phosphorus to plants. Other phosphate compounds such as $Ca_4H(PO_4)_3 \cdot 3H_2O$ and $Ca_{10}(PO_4)_6(OH)_2$ are very insoluble and would therefore provide little in the way of phosphorus to the plants. Some workers state that fertilizer phosphate remains available for some time in the soil (Soper and El Bagouri 1964 and Spratt and McCurdy 1966). A general and slow transformation of the more soluble phosphates to the insoluble phosphates undoubtedly takes place (Lindsay and Stephensen 1959).

B. Residual Phosphorus Studies

Residual phosphorus is present in nearly all soils to a greater or lesser degree, depending on the amounts of fertilizer previously added. There have been few studies on residual phosphorus in Western Canada and therefore the time over which this residual phosphorus is released and thereby beneficial to succeeding crops is not well known.

Ridley and Hedlin (1962) conducted a study on a long term rotation experiment to which phosphorus had been added for 38 years. They found that the total inorganic and extractable phosphorus content of the soil was increased while the organic phosphorus fraction was not affected. The experiment was set-up using 4 year rotations of fallow, wheat, corn and barley. The phosphorus was applied once during the rotation, prior to seeding wheat in the second year of

the rotation. They found a phosphorus response in the first crop (wheat) but no residual effects on succeeding crops. This appears strange when one views the results they tabulated. After 38 years of adding phosphorus (once every 4 years) they show extractable phosphorus values as high as 78 - 98 kg P/ha for some of the plots receiving higher rates of phosphorus. Values this high should certainly show some residual effects on succeeding crops. However, it must be noted that Soper and Racz (1967), in citing work by Doughty et al (1954) Newton et al (1945), and Rennie and McKercher (1959), concurred with Ridley and Hedlin in that little crop response to phosphorus is found except in the year applied.

Dawley (1965) conducted a study on residual phosphorus using a silty clay loam in Saskatchewan. The soil had received 20 kg P/ha for 7 years while in pasture. The fertilized pasture did not respond to the fertilizer phosphorus (Cooke et al). Dawley showed, however, that after the pasture was plowed up and barley sown, the residual phosphorus increased yields. He suggested that the broadcast phosphorus was not available to the hay, but became available to the barley roots when mixed into the surface soil.

Much work has been done on residual phosphorus in the United States. Similar experiments were undertaken in Montana (Campbell 1965), New Mexico (Leamer 1963), and Oregon (Hunter et al 1961). All three soils were calcareous and were on irrigated soils. A 6 year rotation was used with phosphorus (P) rates of 0, 29.1, 58.2, 117.6, and 235.2 kg/ha applied at the beginning of the rotation. In all 3 experiments, crop yields were increased as a result of residual phosphorus uptake; the yields being proportional to the previous rate of phosphorus

applied.

Other workers (Peck et al 1965, Sutton and Larsen 1963, Hutton and Robertson 1961, Weeks and Miller 1948, Salomon and Smith 1956, Prince 1953, Rich et al 1948, Rubins 1953, Smith 1957, Warren 1956, Webb and Pesek 1954, Moschler et al 1957, Ensminger 1960, and Olsen et al 1954), while conducting studies on dryland soils in different areas of the United States also reported a significant yield response to residual phosphorus. Similar results have been reported by workers in various other countries: (Giskin et al 1973, Hughes and Searle 1964, Mattingly 1963, Piper and DeVries 1964, Simpson 1963, Boswinkle 1961, and McAuliffe et al 1951).

Although the large majority of workers report definite yield increases from residual phosphorus in the soil, the length of time maximum yields can be maintained after phosphorus applications are terminated differ somewhat. Some workers have reported maximum or near maximum yields for at least 16 years after phosphorus fertilization was discontinued (Giskin et al 1973). Others have reported maximum yields for 5 years after phosphorus fertilization was terminated. How long maximum yields will be maintained depends upon the length of time phosphorus fertilizer is applied, rates of fertilizer applied, "fixing" capacity of the soil, moisture content, temperature and other soil and weather factors. Some workers contend that the type of fertilizer applied makes a difference in the residual effect of the phosphorus. Boswinkle (1961) showed that the residual effects of superphosphate were greater than rock phoshate when applied at the same rate. However, others have shown that superphosphate increased yields over rock phosphate initially, but the residual effect of the

rock phosphate was greater (Doll et al 1960). Mattingly (1964) showed that where equal amounts of phosphate was added as super and rock, the superphosphate increased total and $NaHCO_3$ - extractable phosphate while the rock phosphate increased total P but not the $NaHCO_3$ - extractable phosphate. After 3 years, however, total and $NaHCO_3$ - extractable phosphate values were very similar for the two sources.

Spratt and McCurdy (1966), working with a clay chernozem, found that even with high residual phosphorus values, maximum yields will not be attained without the addition of some fertilizer phosphorus with the seed. They contend that in the early spring, when the soil is cold, native phosphorus is not readily available and the needs of the seedlings are high. The fertilizer phosphorus, which is readily available and in close proximity with the seed, is readily utilized. They term this a "starter effect" which they claim is evident regardless of the level of available soil phosphorus.

C. Conclusions

When fertilizer phosphorus is added to the soil, fixation of the majority of available phosphorus into relatively unavailable forms usually takes place. The process may be very fast or may take several months depending on the type of soil and various other factors. The release of this fixed fertilizer phosphorus over time may provide available phosphorus to plants after fertilization has been terminated. This is termed available residual phosphorus and its importance is potentially high. The problems, however, are many and vary with the soil types and climatic conditions.

Although a large number of studies have been undertaken with

residual phosphorus, few of these studies have been initiated in Western Canada. Many of those studies which have been carried out appear to agree that phosphorus fertilization over time does increase residual phosphorus and the benefit to subsequent crops is significant. However, because the numbers of studies are few, we lack sufficient data which would enable us to form definite conclusions regarding residual phosphorus in Western Canada. Whether residual phosphorus exists in Alberta soils and whether crops will benefit from it will therefore be the aim of this study.

III MATERIALS AND METHODS

A. Background Material

In 1964 a detailed study was initiated to evaluate the effects on barley yields of fertilizer and soil nitrogen, phosphorus, and potassium. Soil water and some climatic factors were also included in this study. Initially, two Chernozemic soils (sites 01 and 21) were used and in 1965 four additional sites (3 Luvisols and 1 Chernozem) were added. Legal locations and soil classifications are given in Table 1. Particle size analyses using the pipette method were reported by Heapy (1971) for the six sites and are also summarized in Table 1.

Phosphorus rates of 0, 13, 27, 40 and 54 kg/ha were applied in combination with 5 rates of nitrogen and potassium using a central composite design (Table 2). The test crop was Gateway 63 barley. The grain was harvested from the sites and a straw application equalling the amount removed was returned to the soil. After the 1968 crop the fertilizer applications were terminated, but cropping continued through 1973 to evaluate residual effects of the previously applied fertilizers. In 1972 and 1973, blanket applications of nitrogen were applied to all sites.

In the spring of 1971, two years after fertilization was terminated, bulk samples of the 0-15 cm. depth were taken to represent each of the five phosphorus levels at the six sites (Table 2). Note that the plots receiving the 0, 27 and 54 kg P/ha P had received no nitrogen during the 1964 - 1968 period while the 13 and 40 kg/ha plots also received 34 kg N/ha in addition to phosphorus (Table 2). Note also that of the five previous phosphorus treatments sampled, only four were chosen for

TABLE 1

Site details and classification of soils used in residual phosphorus studies.

Site	Legal Location	Sand* %	Silt* %	Clay* %	Textural Class	Soil Classification
01	NE-24-51-25-4	24	46	30	Clay loam	Othic Black Chernozem
03	SE-28-52-21-4	38	44	18	Loam	Orthic Gray Luvisol
05	SE-11-54-22-4	38	36	26	Loam	Eluviated Black Chernozem
21	NE-24-40-27-4	57	25	18	Sandy loam	Eluviated Black Chernozem
23	NW-29-41-23-4	44	44	12	Sandy loam	Orthic Gray Luvisol
25	NW-21-42-23-4	44	47	9	Sandy loam	Orthic Gray Luvisol

* Particle size analyses for 0 - 15 cm depth

TABLE 2

Central composite design showing nitrogen, phosphorus and potassium treatments applied in the field from 1964 - 1968.

Phosphorus (kg/ha)	Potassium (kg/ha)	Nitrogen (kg/ha)				
		0	34	67	101	134
0	0	X*				X
	13					
	27			X		
	40					
	54	X				X
13	0					
	13		X*		X	
	27					
	40		X		X	
	54					
27	0			X		
	13					
	27	X*		X		
	40					
	54			X		
40	0					
	13		X*		X	
	27					
	40		X		X	
	54					
54	0	X*				X
	13					
	27			X		
	40					
	54	X				X

* Bulk soils samples selected for these treatments

the greenhouse study (0, 13, 27 and 54 kg/ha). It was thought that the maximum practical application rate for farmers would be the 27 kg/ha P and thus only one higher rate, the 54 kg rate, was included against which the other three previous phosphorus rates (0, 13 and 27 kg/ha) could be compared. A lack of space in the greenhouse also helped in deciding against the use of the 40 kg rate.

The samples were taken by digging furrows 15 cm deep across each of the plots. These samples were then passed through a 0.5 cm screen and thoroughly mixed. Stones, straw and other debris were discarded. A small representative subsample of approximately one kilogram in size was taken from each of the larger bulk samples. These subsamples were further crushed to pass through a two mm screen and used for physical and chemical analyses.

B. Laboratory and Greenhouse Work

Using the bulk samples collected in 1971, a greenhouse study was initiated. The reason for this study was to determine to what extent previously applied phosphorus fertilizer increased the phosphorus levels in the soil and to what extent greenhouse crops would benefit from the residual phosphorus. Laboratory analyses, such as extractable and total phosphorus in the soil, and plant phosphorus as well as continual cropping in the greenhouse, were used to show the changing phosphorus status in the soil and the effect this had on the consecutive crops. It was further hoped that the study would show the minimum concentration of extractable phosphorus for each soil which could produce maximum crop yields.

Soils from each of the four previous phosphorus treatments from each of the six sites were used in the greenhouse experiment. These

24 treatments were arranged in a randomized block design with three replicates. Each treatment consisted of a pair of pots located side by side, one pot receiving no further phosphorus additions, the other receiving phosphorus at the commencement of each greenhouse crop. Thus, the effect of the previous P treatments on the various sites could be evaluated in three ways:

(1) yield of the pot which received no further phosphorus additions in the greenhouse

(2) increase in yield when phosphorus was added in the greenhouse; i.e. the difference in yields for the 0 and plus phosphorus rates

(3) the relative yield i.e. (the yield of the pot with 0 phosphorus)/(yield of the pot with added phosphorus)

Each of the pots contained 1100 gms (oven dry basis) of soil. Two phosphorus rates (0 and 30 ppm P as KH_2PO_4) were applied in the greenhouse to the four previous treatments. Nitrogen (100 ppm N as NH_4NO_3 and $(NH_4)_2SO_4$), potassium (80 ppm as KH_2PO_4 and K_2SO_4, and sulfur (30 ppm as K_2SO_4 and $(NH_4)_2SO_4$)) were applied to all pots. The four nutrients were applied in solution form in a band slightly beneath the seeds. Six barley seeds (Galt for the first crop and Olli for the remainder) were planted and thinned to three seedlings after emergence. Soils moisture was controlled by weighing and watering the pots to 1/3 atm. Four consecutive greenhouse crops were run over a period of 9 - 10 months. The first crop commenced in the middle of October and continued to December 1st, 1972. The second crop commenced December 20th and ran until the first week of February, 1973. The third crop went from March 1st to April 15th and the fourth crop went from May 1st until June 15th, 1973. Between each crop the soil was allowed to air dry in the pot. A soil sample

was taken for determination of extractable phosphorus. The remaining soil was then passed through a 0.5 cm screen, mixed, returned to the same pot and reseeded. After the first crop, the roots were mostly discarded when the soil was passed through the screen. In later experiments as many roots as possible were returned to each pot.

Total phosphorus, extractable phosphorus by two methods (Miller and Axley (1956) and Olsen (1954)) and pH of the soil were measured prior to the first greenhouse experiment. After each of the four greenhouse experiments extractable phosphorus was measured by the Miller and Axley method only. The dried plant material from each of the experiments was ground to pass through a 20 mesh screen. Phosphorus content was then determined on this material.

All analyses done in this study were in duplicate and average values recorded.

C. Methods of Chemical Analyses

The pH of the initial samples was determined using the standard paste method. Total phosphorus was extracted by a wet digestion procedure as outlined by Pawluk (1967), except that the sample was ignited at 600° C instead of 900° C. The procedure is described in Appendix A-1. Phosphorus in the extract was determined by the ascorbic acid-reduced molybdophosphoric blue color method in H_2SO_4 system (Watanabe and Olsen 1965), as outlined in Appendix A-2. Phosphorus was extracted by the Miller and Axley (1956) (0.03 M NH_4F and 0.015 M H_2SO_4), and Olsen (1954) (0.5 M $NaHCO_3$) methods, except that the ascorbic acid-reduced molybdophosphoric blue color method in H_2SO_4 system was used for the colorimetric determination of phosphorus (see Appendix A-2). The phosphorus content of the plant material was

determined following digestion in perchloric acid (Isaac and Kerber 1971) as outlined in Appendix A-3.

IV RESULTS AND DISCUSSION

The soils used in this study were taken from field plots which had received various rates of phosphorus fertilizer for four or five years. The phosphorus applications were terminated and two crops of barley grown before the samples were taken. We attempted to evaluate residual phosphorus in the soil by chemical methods and plant growth.

A. Residual Effect as Revealed by Chemical Analysis

1. Total Phosphorus

The total phosphorus content of the soils prior to the first greenhouse experiment showed a slight increase as the previous P rates increased from 0-54 kg/ha (Table 3). In most instances an increase occurred between the 0 and 27 kg rates and in all instances between the 27 and 54 kg rates. Between the 0 and 13 kg rates and the 13 and 27 kg rates, little or no increase is evident.

The fact that there is little evidence of residual effect at the 13.4 or even 26.8 rates is partly explained by the precision of the determination relative to the amount of phosphorus added. For example, the average total phosphorus values frequently represent two values varying by 25 to 50 ppm. The lower rates of phosphorus added expressed as ppm and disregarding crop uptake, were of the order of 25 to 50 ppm. Hence, the sensitivity of this method for detecting residual phosphorus in the soil would appear to be very low.

Although previous phosphorus treatments had little effect on the total phosphorus, there is a very clear difference in total phosphorus amongst the different soils. The three Chernozemic soils (site 01, 05 and 21) have very much higher total phosphorus values than the three Luvisolic soils. As will be seen later however, the high total phos-

TABLE 3

Total phosphorus (ppm) on the soil samples prior to the first greenhouse experiment.
(Average of 2 determinations).

Previous P (kg/ha)	01	03	05	21	23	25	Average
0	780	260	830	835	460	575	623
13	760	270	920	725	500	600	630
27	775	285	840	885	590	615	665
54	840	520	895	975	625	650	750
Average	789	336	871	885	529	610	

phorus in the soils does not mean a higher plant extractable phosphorus; in fact, in these soils the relationship tends to be inverse.

2. Extractable Phosphorus

There was a definite increase in extractable P at all sites as a result of adding phosphorus fertilizers for several years (Fig. 1-3, upper curve, and Appendix A-5). Usually the extractable phosphorus levels increased as the previous phosphorus applications increased from 0 to 54 kg/ha/yr. Further, the greatest increases were observed for the sites (21, 23, 25) which were originally highest in extractable phosphorus. (Appendix A-5).

However, while a general increase in extractable phosphorus occurred for all sites, little or no increase was noted between the 0 and 13 kg/ha rate of previously applied phosphorus. In fact, in some instances, a slight decrease occurred. The reason for this may be that when the previous phosphorus fertilizer applications occurred, no nitrogen was applied to the plots receiving the 0, 27 and 54 kg/ha rates of phosphorus whereas the plots which received the 13 kg/ha rates also received 34 kg of nitrogen (Table 2). This added nitrogen may have increased crop uptake of applied P to the extent where the extractable phosphorus in the soil did not increase.

Extractable phosphorus in the soil prior to the 1st greenhouse crop was measured by the Miller and Axley (1956) and Olsen (1954) methods (Fig. 4 and Appendix A-6). A high correlation (r=0.90) was found between the results of the two methods and it was therefore decided to use only the Miller and Axley method for all remaining determinations of extractable phosphorus. The high correlation between the two methods was also found by Robertson et al (1968) and Omanwar

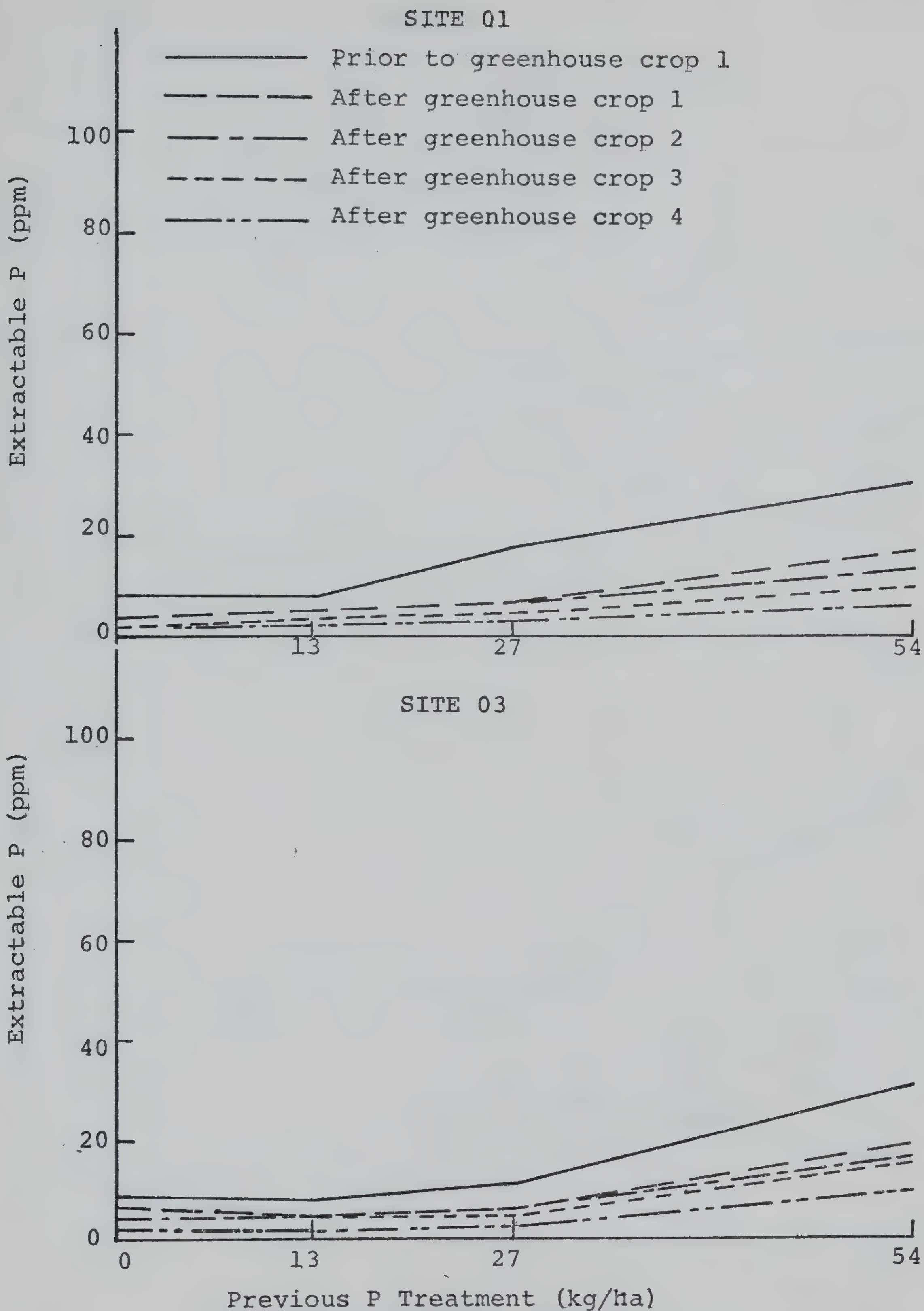


Figure 1 (top and bottom) Extractable phosphorus in the soil by the Miller and Axley method

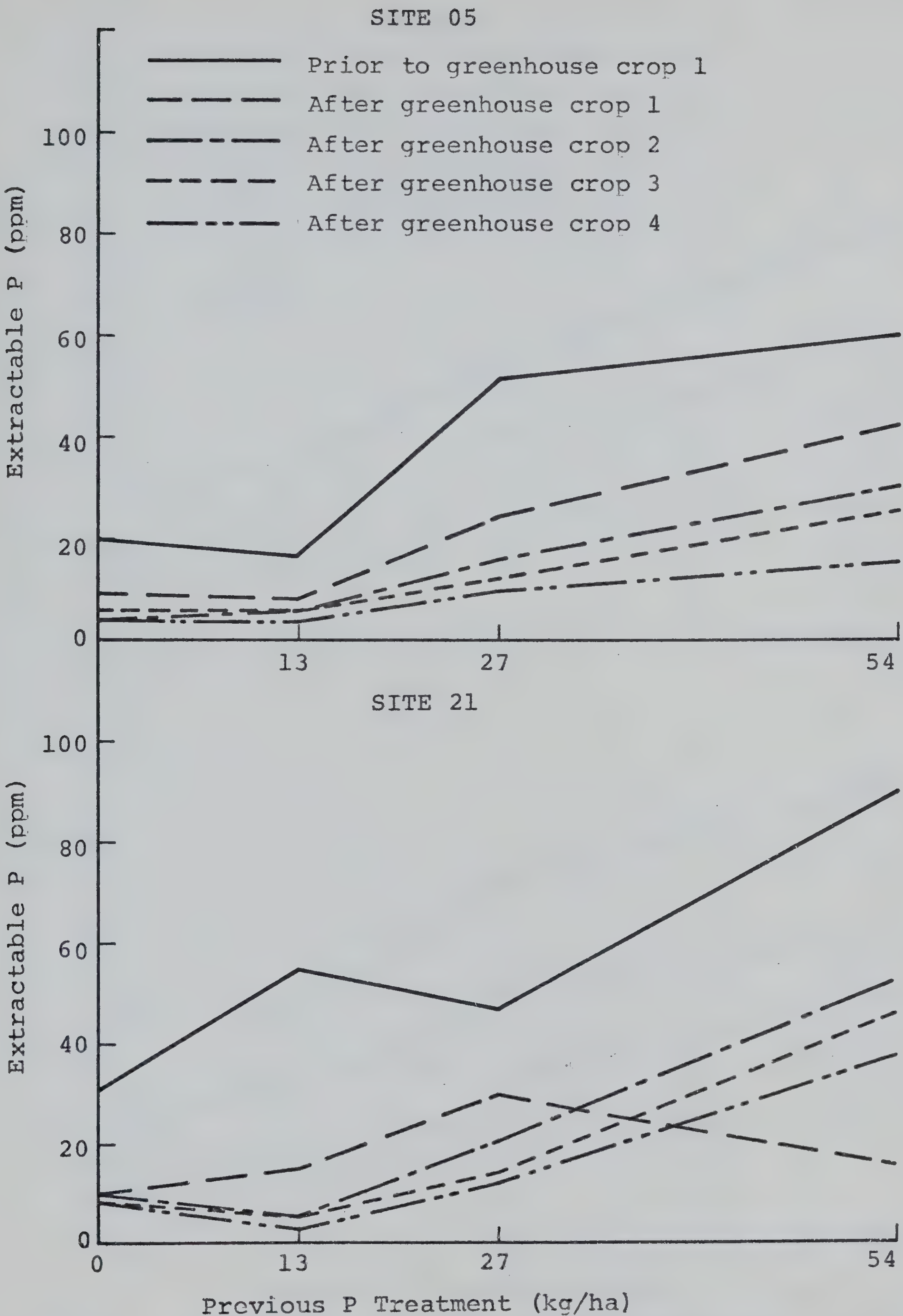


Figure 2 (top and bottom) Extractable phosphorus in the soil by the Miller and Axley method

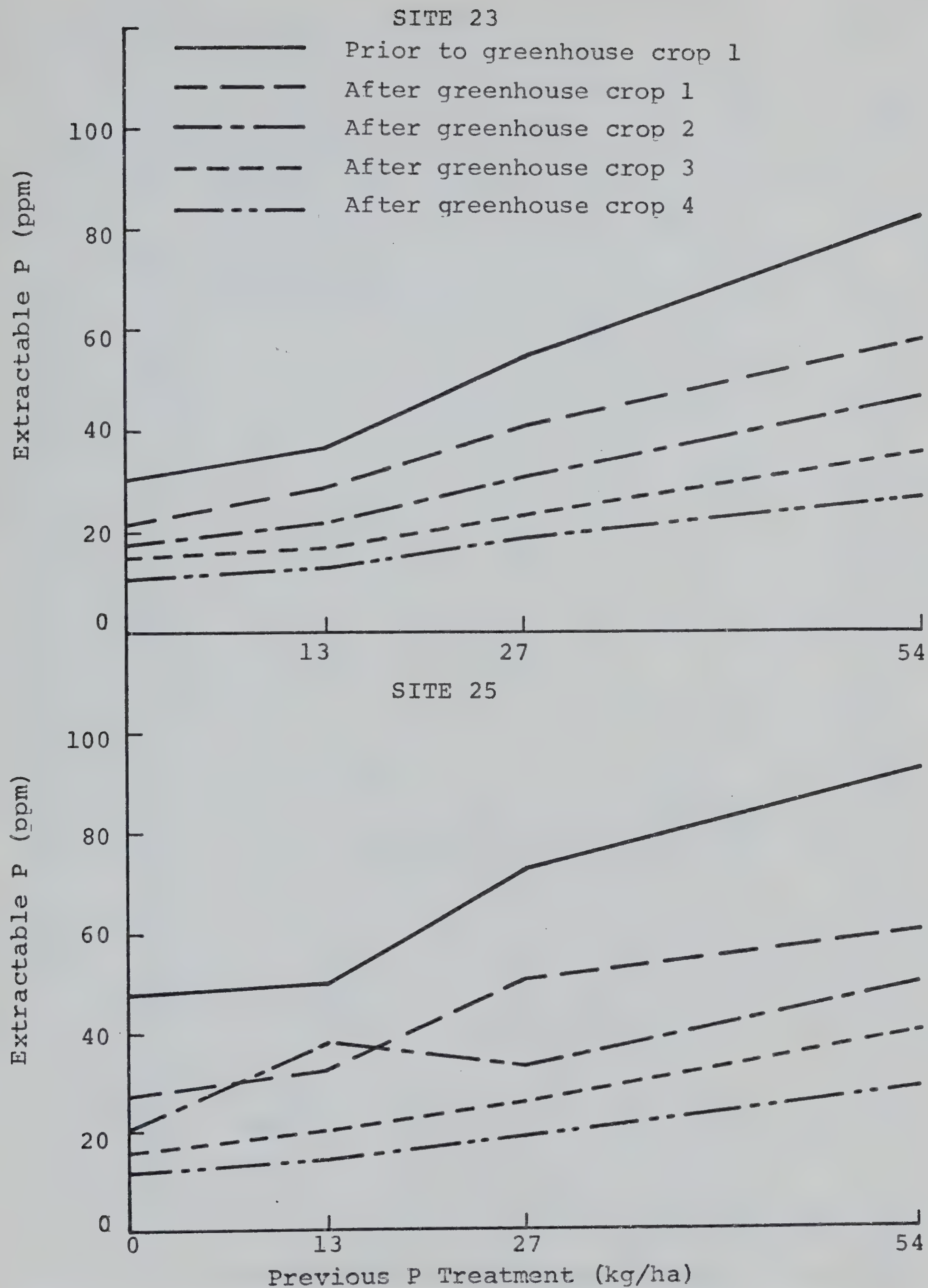


Figure 3 (top and bottom) Extractable phosphorus in the soil by the Miller and Axley method

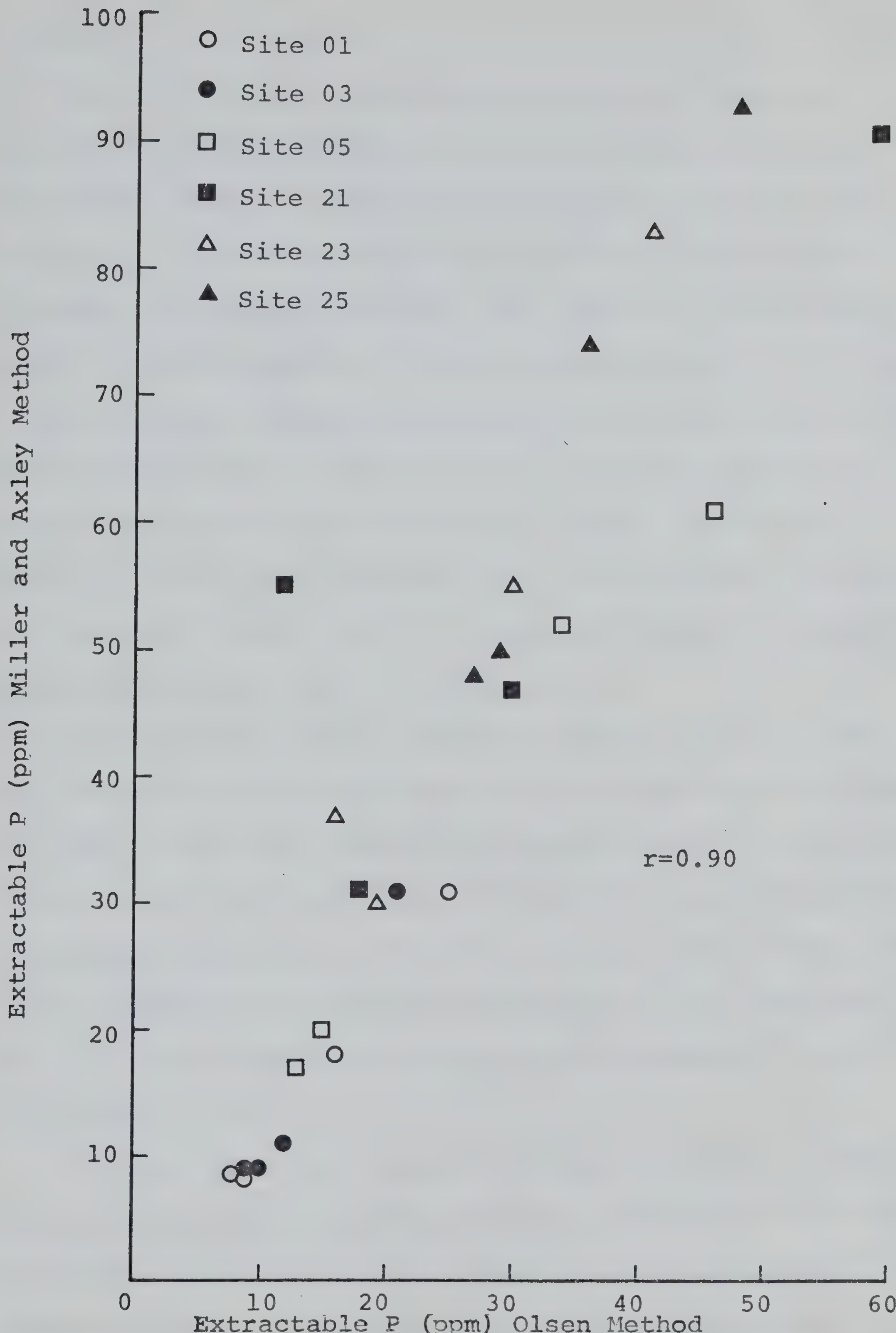


Figure 4: A relationship between levels of extractable phosphorus by two methods

(1971).

With each successive greenhouse crop, there was a general decrease in extractable phosphorus for all sites and all previous phosphorus treatments. This relationship showed particularly well for site 23; for each succeeding crop there was a nearly parallel decrease in extractable phosphorus. The other sites showed similar trends but with exceptions, the main one being for site 21. For the second greenhouse experiment, an extractable phosphorus value of 16.2 ppm was recorded for the soil previously receiving phosphorus at 54 kg/ha. The value is obviously anomalous (Figure 2 - bottom) and must have resulted from a sampling error. Unfortunately, by the time this value was obtained, the third greenhouse crop was in progress and a duplicate soil sample could not be taken.

For three sites (01, 03, 05), the extractable phosphorus level was reduced by the end of the fourth crop to a similar level of about 5-10 ppm for nearly all the previous phosphorus rates. For sites 21, 23 and 25, the extractable phosphorus levels had not been reduced to this level, presumably because of their initially higher values. With further cropping it is probable that the soils of these three sites (21, 23, and 25) would also reach extractable phosphorus values of approximately 5 ppm.

We can see then that phosphorus additions to a soil over several years does increase extractable phosphorus. The extent to which the extractable levels are increased by phosphorus fertilization is apparently related to both rate of phosphorus additions and soil properties. The extractable phosphorus is in turn removed by the growing of several crops. This extractable phosphorus which is

increased by fertilization and later removed by crops can be referred to as residual phosphorus.

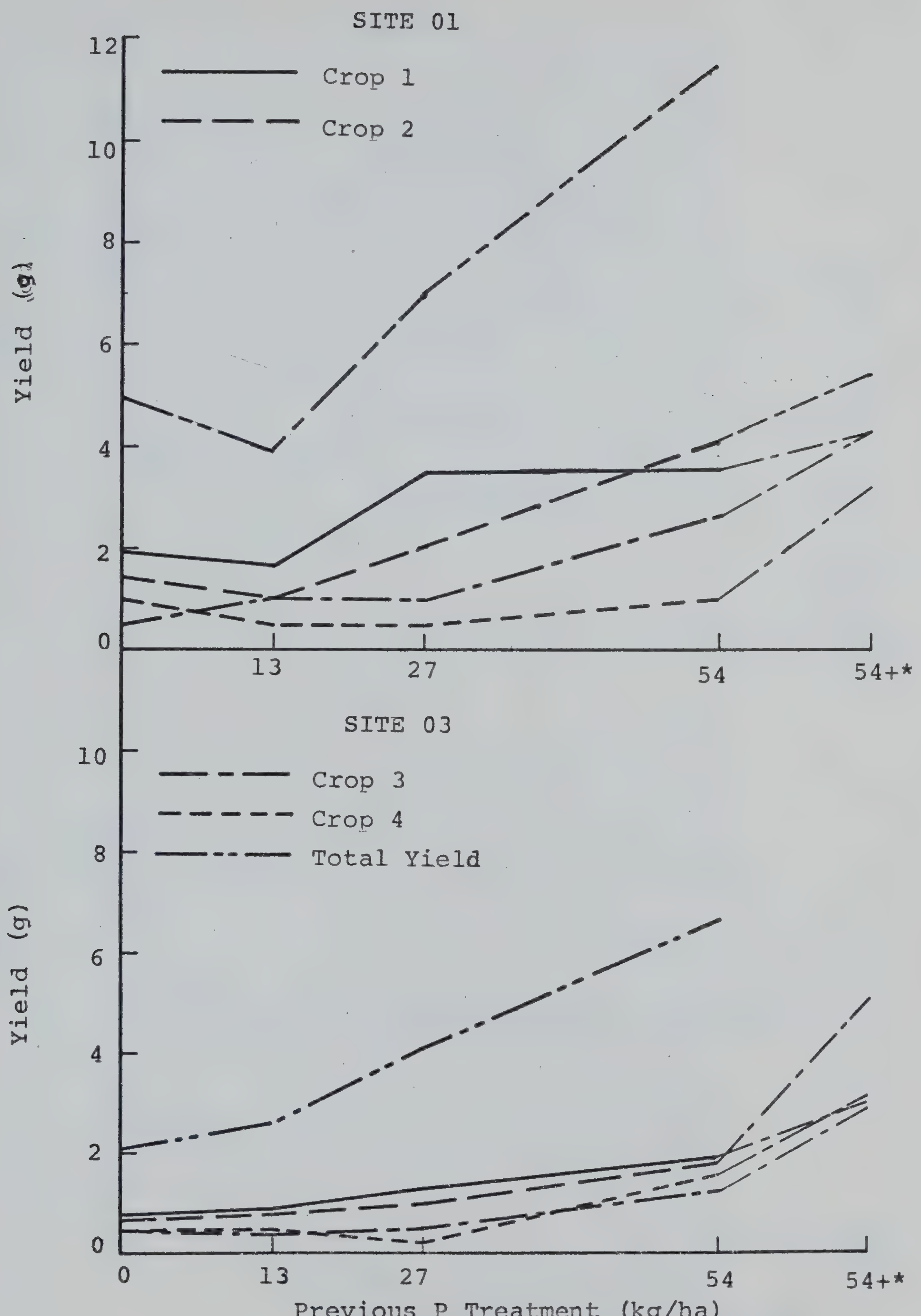
B. Residual Effect as Revealed by Greenhouse Crops

1. Dry Matter Yield

i. On Previously Unfertilized Soils

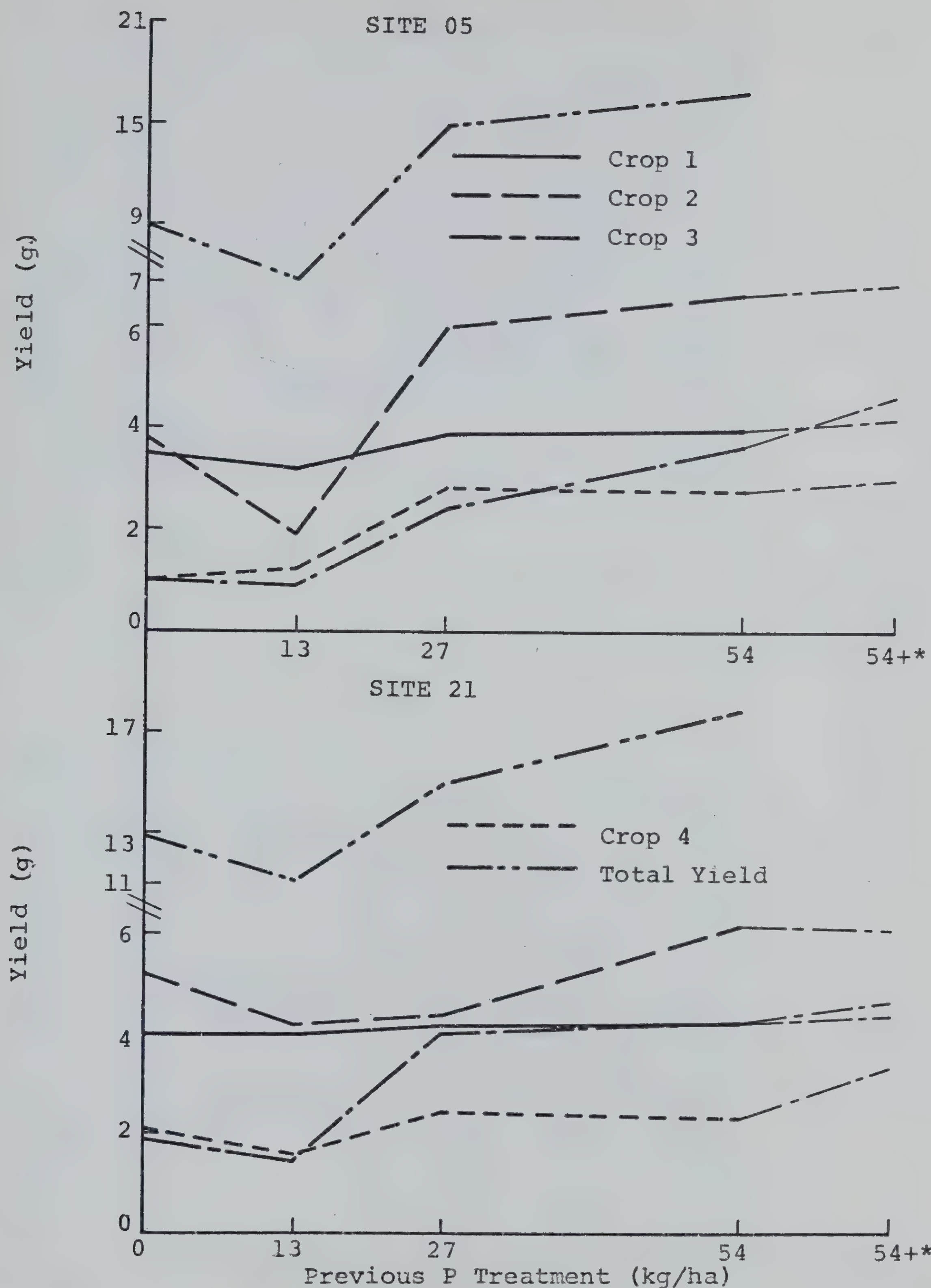
The total yields of the four greenhouse crops were calculated for each of the four previous phosphorus rates. The "unfertilized" soils mentioned in the above heading refers to the control soil or the previous phosphorus rate of 0 kg/ha.

The total yields for the previously unfertilized soils ranged from 2 to 15 g/pot (Figs 5-7, Appendix A-7, and Plates 1-6). As the extractable phosphorus increased (Figs 1-3 and Appendix A-5) the yield also increased with two exceptions. Site 01 and 03 soils had the same extractable phosphorus level (about 5 to 10 ppm), but site 01 outyielded site 03 by approximately 2.5 times. It would appear that even though the extractable phosphorus values for the two soils were the same, the plants in the site 01 soils were able to take up more phosphorus than could the plants in site 03 soil, that is the phosphorus in site 01 was more available to the plants than was the phosphorus in site 03. Several reasons for the difference can be suggested. First, site 01 soil is much higher in organic matter and total phosphorus (Table 3). Hence, a significant amount of phosphorus, which is not extracted by the laboratory method used may have been mineralized from the organic matter during cropping and hence used by the crop. Secondly, soil from site 01 may have provided a better growth medium (water, aeration, fertility) than that from site 03, thus allowing for better root growth and/or phosphorus uptake, in spite of the same extractable



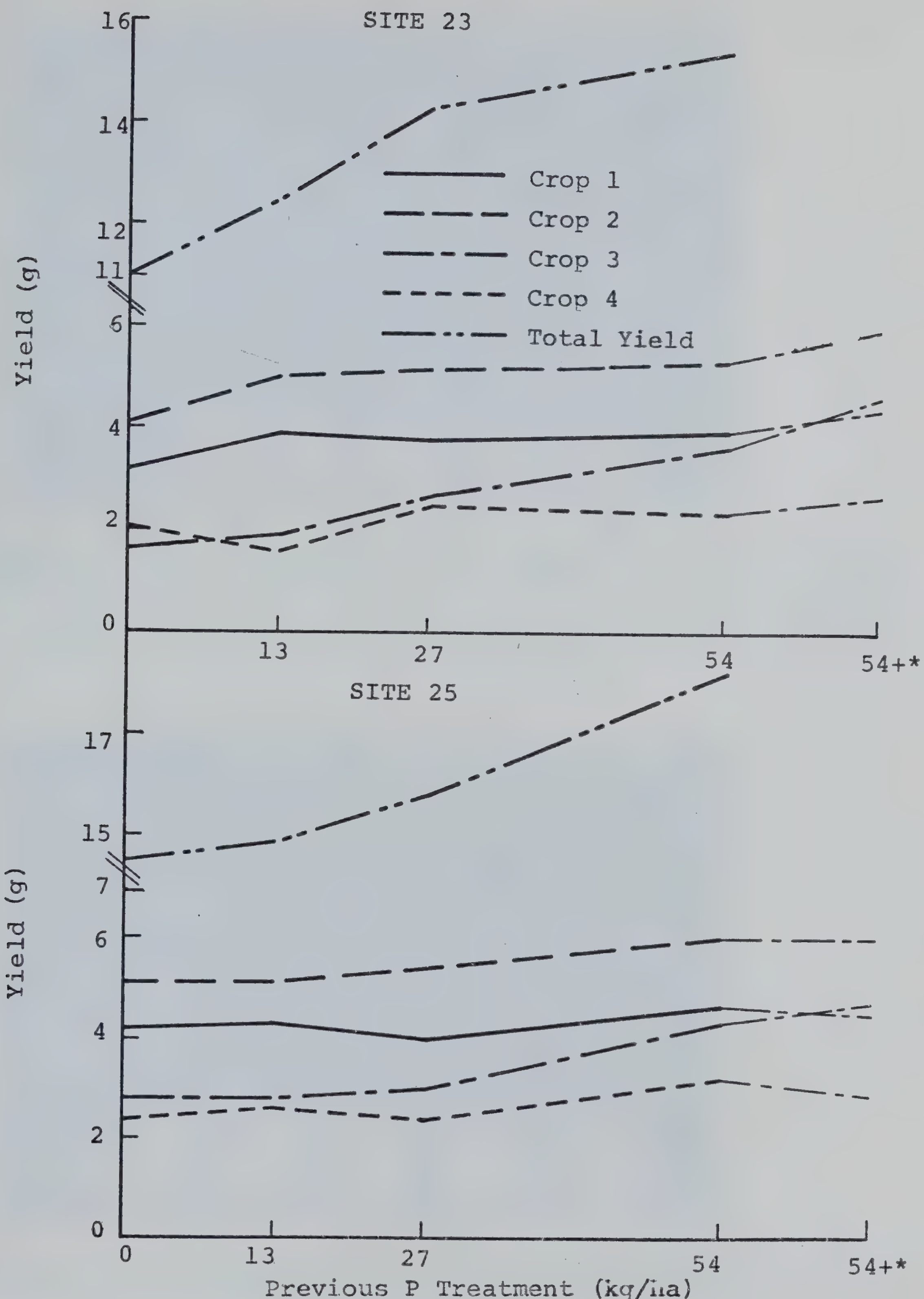
* 30 ppm P added in the greenhouse

Fig 5 (top and bottom) Dry matter yields of barley grown in the greenhouse



* 30 ppm P added in the greenhouse

Fig 6 (top and bottom) Dry matter yields of barley grown in the greenhouse



* 30 ppm P added in the greenhouse

Fig 7 (top and bottom) Dry matter yields of barley grown in the greenhouse

Plate 1: Growth of barley in the fourth greenhouse experiment on soil of site 01. Soil in the pots received (L to R) 0, 12, 24 and 48 lb P/acre (0, 13, 27 and 54 kg/ha). The soil on the right received 48 lb P/acre in the field and additional P in the greenhouse.

Plate 2: Growth of barley in the fourth greenhouse experiment on soil of site 03. Treatments the same as for Plate 1.

Plate 3: Growth of barley in the fourth greenhouse experiment on soil of site 05. Treatments the same as for Plate 1.

Plate 4: Growth of barley in the fourth greenhouse experiment on soil of site 21. Treatments the same as for Plate 1.

Plate 5: Growth of barley in the fourth greenhouse experiment on soil of site 23. Treatments the same as for Plate 1.

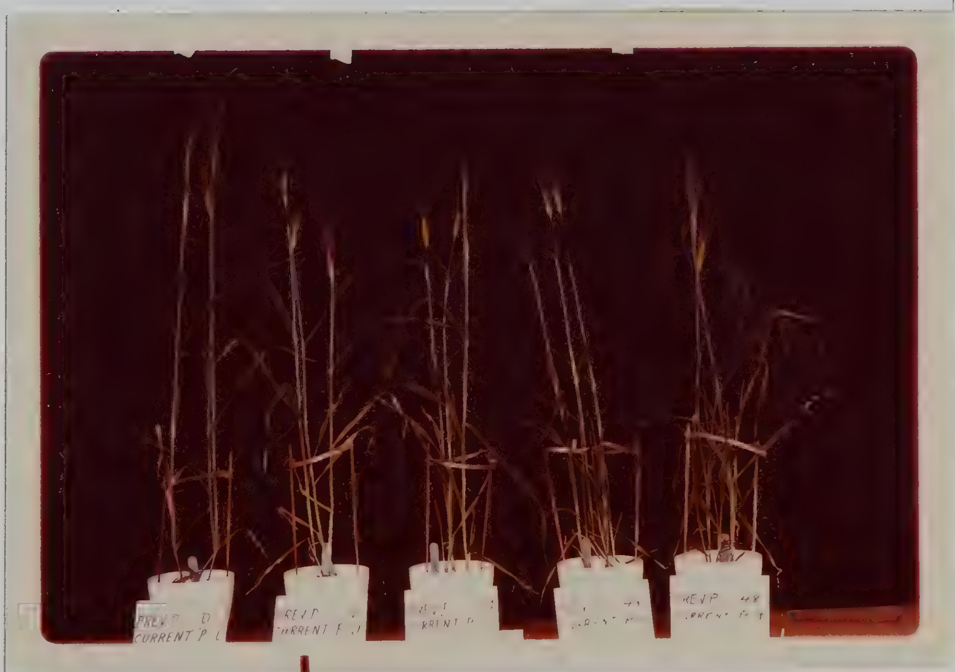


Plate 6: Growth of barley in the fourth greenhouse experiment on soil of site 25. Treatments the same as for Plate 1.

phosphorus level. Thirdly, the inorganic forms of phosphorus were possibly different, which might result in unequal availability to plants in spite of similar extractability. Omanwar (1971) did some work on soil from site 03 and soil similar to site 01 and found significant differences in inorganic forms of phosphorus between the Chernozem and the Luvisol. Further study of the two soils would have to be undertaken before more conclusive answers could be obtained. The important point to note is that extractable phosphorus and available phosphorus are not necessarily one and the same. The second exception noted is between site 21 and 23. While both sites tested near 30 ppm of extractable phosphorus, site 21 outyielded site 23 by a small margin. The explanation presented above may also apply here. One small note of interest is that in both of the above instances, when two sites had similar extractable P values, the Chernozemic soils (01, 21) outyielded the Luvisolic sites (03, 23).

ii. On Previously Fertilized Soils

For all of the six soils total yield increased as the previous phosphorus rate increased (Figs. 5-7 and Appendix A-7). The increases ranged from four to eight g/pot. Consider, for example, site 03. The total yield for the previous phosphorus rate of 13 kg/ha was 2.6 g/pot. The total yield for the 54 kg/ha previous phosphorus rate was 6.7 g or an increase of approximately 4 g when the rate was increased from the 13 to 54 kg/ha rates. With the exception of site 03, the absolute increase was greater on those sites originally low in extractable phosphorus (sites 01 and 05). However, if expressed on a relative basis (% yield increase = $\frac{\text{highest y} - \text{check y}}{\text{check y}}$ (100) we find that all of the

low extractable phosphorus sites show much higher increases than do the high testing sites (21, 23, 25). Site 03, while showing a smaller absolute increase than sites 01 and 05, shows a very much higher percentage increase than the other two low testing sites. It is noteworthy that site 03 shows a higher percentage increase than does site 01, even though the two sites had the same extractable P values. Sites 21 and 23, which also had similar extractable phosphorus values, showed very similar percentage increases also.

A reduction in the total yield occurred between the 0 and the 13 kg P/ha rate for sites 01, 05 and 21. During the years when the fertilizer applications took place, the plots receiving the 13 kg/ha rate also received 34 kg N/ha while the other rates (0, 27 and 54 kg/ha P) received none. This added nitrogen may have encouraged the barley plants to take up more phosphorus than would have occurred if only 13 kg P/ha had been added. The higher removal of phosphorus from the soil could have lowered plant available phosphorus in the soil and hence account for the lower yields in the greenhouse. This explanation could certainly apply to the soils with lower extractable phosphorus (site 01 and 05). The yield decrease was not as severe for site 21 and may be due to the originally higher extractable phosphorus level for this soil. Why the same observation was not made on site 03 is not clear.

While there is a general yield reduction from greenhouse crop number 1 to crop number 4, paralleling the extractable P reductions, a great deal of variation exists among the four crops. Crop number 2 is especially anomalous because for most cases it outyields crop number 1. There are several reasons which could account for this increase rather

than the expected decrease in crop yield. The first greenhouse crop was Galt barley and was sown on approximately the first of November. The later greenhouse crops consisted of Olli barley and the second one was sown on December 22nd. The second crop, in addition to being a different variety, was also given more hours of light and a higher temperature. Subsequent crops were grown in the spring and early summer when they were able to receive more natural sunlight which may also account in part for the variation among the crops. An attempt was made to keep greenhouse conditions uniform for the four crops, but this was difficult to accomplish because of the number of people using the greenhouse space and the seasons over which the four greenhouse crops extended.

iii. Effect of Adding Phosphorus in the Greenhouse

As mentioned in the Materials and Methods, for each of the 24 treatments (6 sites x 4 previous phosphorus rates) in the greenhouse, one pot received no further phosphorus additions while a second pot received 30 ppm P prior to each greenhouse crop. To this point, only the yields on the former have been discussed.

For the soils of sites 01 and 03, the phosphorus applied in the greenhouse markedly increased total yields over those obtained from soils receiving only the 54 kg/ha previously (Figs. 5-7 and Appendix A-7). Thus the four or five field additions of phosphorus at a rate of 54 kg/ha did not increase the extractable (available) phosphorus sufficiently to permit maximum growth of the four greenhouse crops. However, as noted in the previous section, the previous phosphorus rates of 27 and 54 kg/ha did provide some residual effect. For the soils of sites 05, 21, and 23, the supplemental phosphorus added in

the greenhouse increased total yields to a limited extent. Even though the four or five field applications of phosphorus raised the extractable phosphorus level to 60 - 90 ppm, the available phosphorus level was not sufficiently high to maximize growth of the four greenhouse crops. For the soil of site 25, the supplemental phosphorus added in the greenhouse did not increase yields over those produced on the soil which had received 54 kg/ha for four years in the field. The residual phosphous increased the extractable (available) phosphorus sufficiently so that supplemental phosphorus in the greenhouse was not beneficial. The results for the soil for site 25 are contrary to the view of Spratt and McCurdy (1966) that added phosphorus at the time of seeding will produce yield increases regardless of the content in the soil.

2. Phosphorus Content of the Plant Material

The phosphorus content of the barley was determined for five greenhouse treatments, the four receiving no added phosphorus and the one which had in the field received 54 kg P/ha and in the greenhouse 30 ppm phosphorus prior to each crop.

The phosphorus content of the plant tissue was affected to varying degrees by previous phosphorus applications (Figs. 8-10 and Appendix A-8). This is shown especially well when the average P column (Appendix A-8) is considered. For sites 01 and 03, there is little effect of previous phosphorus applications on the phosphorus content. For sites 05, 21, 23 and 25, the phosphorus content tends to increase as previous phosphorus rates increase. Sites 01 and 03 originally tested low in extractable phosphorus in the soil while sites 05, 21, 23 and 25 originally tested somewhat higher. This may offer some explanation

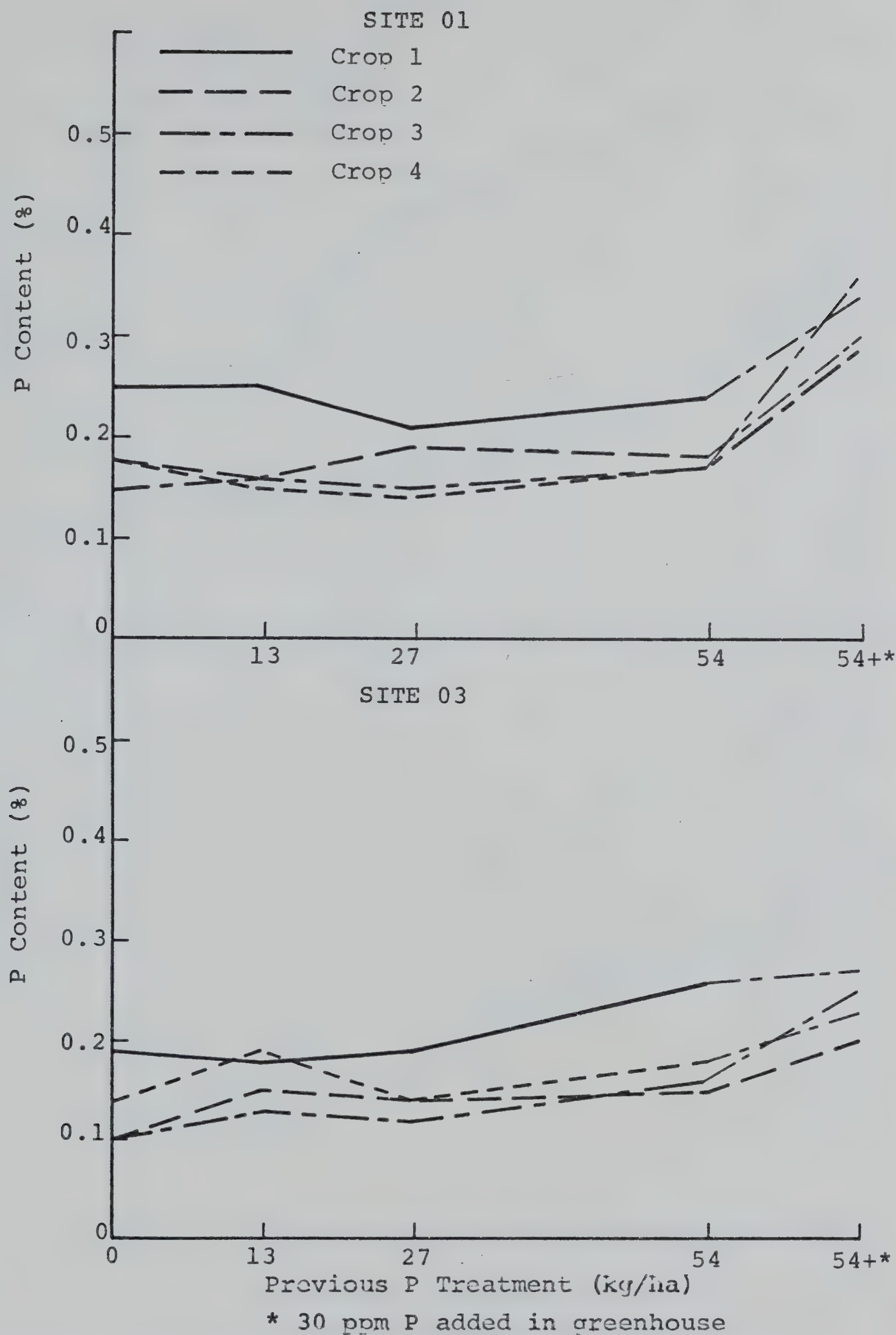


Figure 8 (top and bottom) Phosphorus content of barley plants grown in the greenhouse

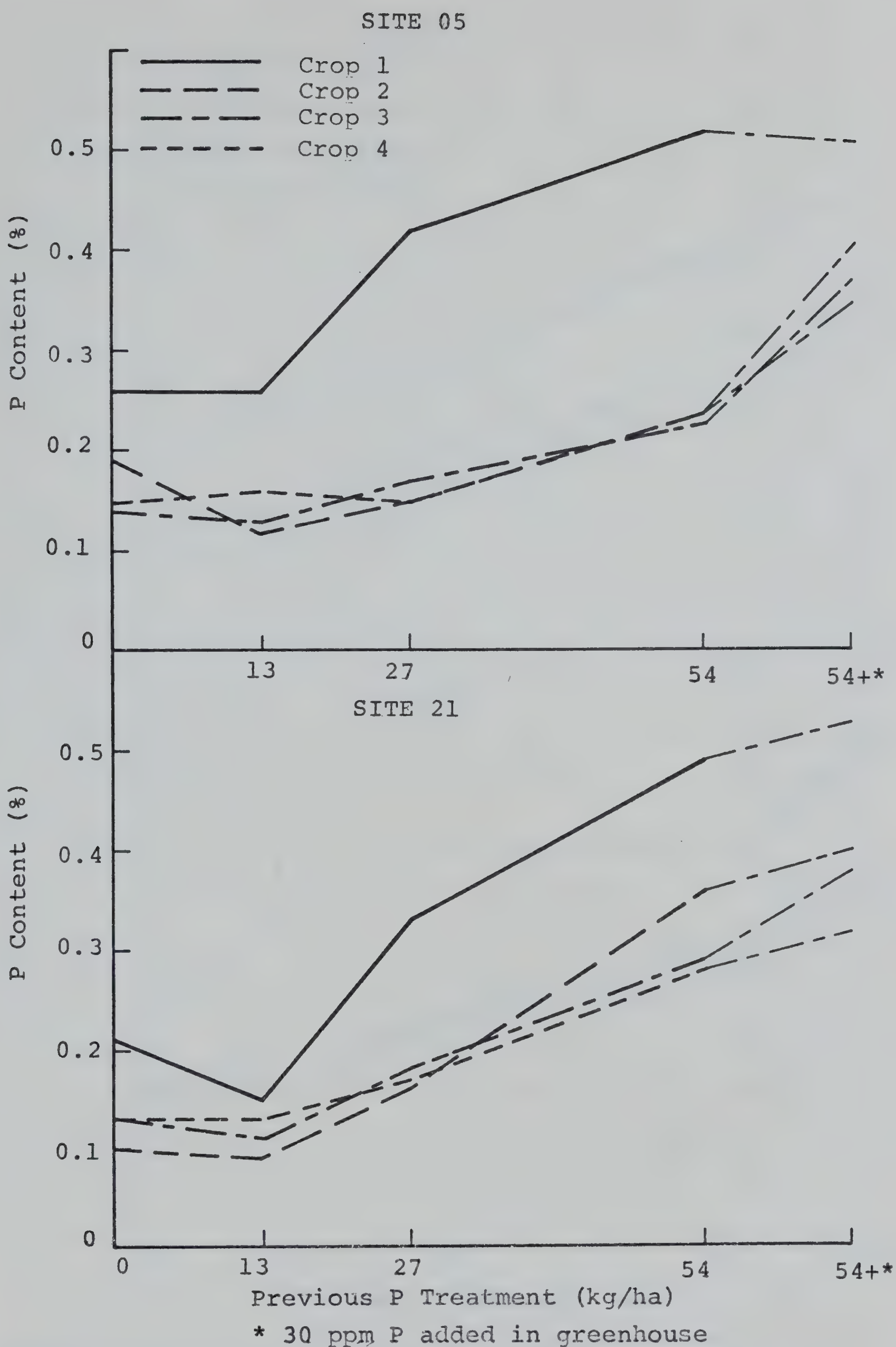
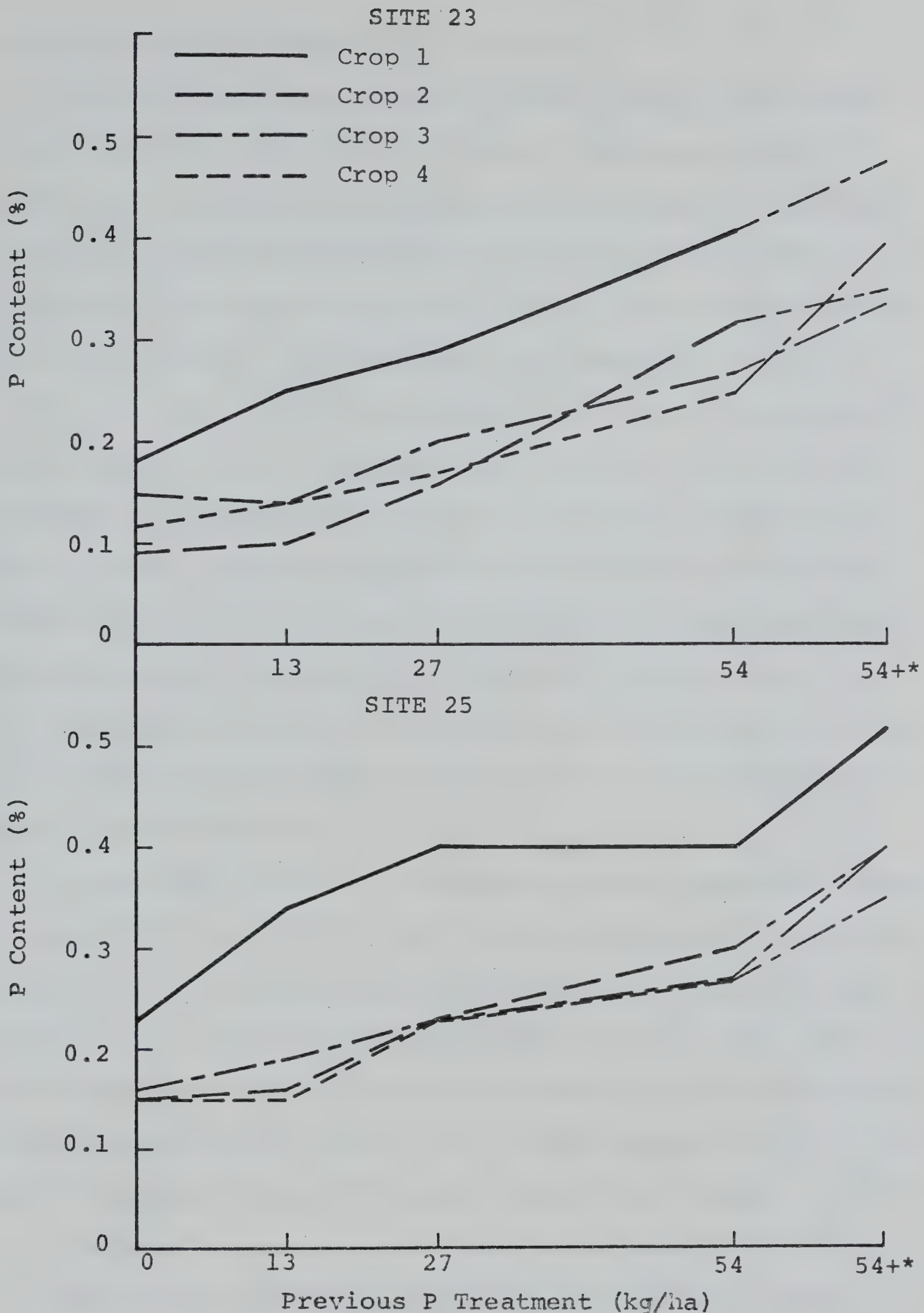


Figure 9 (top and bottom) Phosphorus content of barley plants grown in greenhouse



* 30 ppm P added in greenhouse

Figure 10 (top and bottom) Phosphorus content of barley plants grown in the greenhouse

for sites 01 and 03 showing little or no trend.

There is a definite decrease in P content from the first to the fourth crop (Figs. 8-10 and Appendix A-8). This agrees with the trends shown for dry matter and extractable phosphorus and shows that as the phosphorus is removed from the soil by successive cropping, the phosphorus in the plants grown on the soil receiving the previous phosphorus treatment of 0 and 13 decreased to a minimum level of 0.10 - 0.15% by the third crop for all six sites. While this decrease to a low P content is understandable for sites 01 and 03, which were originally low in extractable phosphorus, it is difficult to understand for sites 23 and 25, which originally had high extractable phosphorus and which after three or four greenhouse crops still had higher extractable phosphorus levels than were initially present in sites 01 and 03. By the third crop, the plants on the soils from sites 01 and 03 were showing definite deficiency symptoms while the plants on the soils from sites 23 and 25 were not.

As mentioned previously, a reduction in percent phosphorus occurred from crop 1 to crop 2 for all sites and previous phosphorus treatments. However, while some sites show a progressive decrease with each crop, others do not. Sites 01 and 03, both originally low in extractable phosphorus, show a more or less stepwise reduction while the remaining sites, which originally tested higher in extractable phosphorus, do not show this stepwise decrease to the same degree. Crop 2 seems to be the key to this difference.

For sites 01 and 03, the phosphorus content decreases steadily through to the third crop while for sites 21, 23 and 25, and the two highest previous phosphorus treatments of 05, the phosphorus content

decreased dramatically from the first to the second crop. For the third crop there is then a very slight decrease or, in some cases, a slight increase in the phosphorus content over the second crop. The large decrease in phosphorus content from the first to the second crop was unexpected and may be partly explained by variations in growing conditions. While the four crops were growing, an attempt was made to keep the greenhouse conditions similar. For crop number 2, however, the plants received extra hours of light and the greenhouse compartment was at a higher temperature than for the other crops. For sites 05, 21, 23, and 25, the second crop had very high dry matter yields and very low P contents. It seems then that the conditions in the greenhouse encouraged very rapid growth for the barley plants and that they were unable to absorb phosphorus fast enough to compensate for the rapid growth rate. The reason that crops grown on site 01 and 03 soils did not experience the sharp decrease in phosphorus content for crop number 2 may have been that the residual phosphorus levels were low and fast growth would be unlikely.

It appears that "luxury consumption" of phosphorus occurred in certain cases. In one particular instance (site 25 - crop 1) a phosphorus content of 0.50% was obtained which was somewhat higher than that needed to attain a maximum yield. Other examples of this "luxury consumption" included: site 01 - crop 1, site 05 - crop 1 and 4, site 21 - crop 1, 3, and 4, site 23 - crop 2, 3, and 4, and site 25 - crop 2.

A steady decline in phosphorus content occurred over the four crops for the soils of sites 05, 21, 23 and 25, which had received the highest previous phosphorus rate and also had 30 ppm phosphorus added prior to each greenhouse crop i.e. treatment 54+ (Figs. 9 and 10).

This is curious as each of these treatments received what should have been more than adequate amounts of phosphorus. Perhaps the continuous cropping produced other limitations on the soil which in turn caused less phosphorus to be taken up. Ridley et al, (1974) in citing work by Bingham and Barber (1960), Burleson et al 1961, and Melton et al (1970), showed that when high rates of phosphorus were drilled with wheat, yields were reduced, possibly due to a phosphorus induced micronutrient imbalance or immobilization. This may have been a factor with the high phosphorus rates used in this study.

Dry matter yields and nutrient contents of plant tissue are affected simultaneously though to varying degrees, by nutrient availability in the soil. Hence, it is common practice to calculate nutrient uptake (yield x nutrient content) to obtain a plant measure of nutrient availability. Because nutrient uptake integrates both yield and nutrient content, it tends to exhibit less variability than do either of the other two parameters. Hence, phosphorus uptake for plants grown on the soils which were not fertilized in the greenhouse were calculated from the yields and the phosphorus contents.

The phosphorus uptake generally increased for each site and crop as the previous phosphorus treatment increased (Figs. 11-13 and Appendix A-9). By combining the yield and phosphorus content data, a clearer separation among crops on a given site was obtained than for either the yield data or phosphorus content data alone.

In some instances the results do not show the general increase mentioned above. For site 01 - crop 1 and 2; site 05 - crop 1, 2 and 3; site 21 - crop 1, 2, 3 and 4; and site 23 - crop 4, the phosphorus uptake was lower when the previous phosphorus rate was 13 kg P/

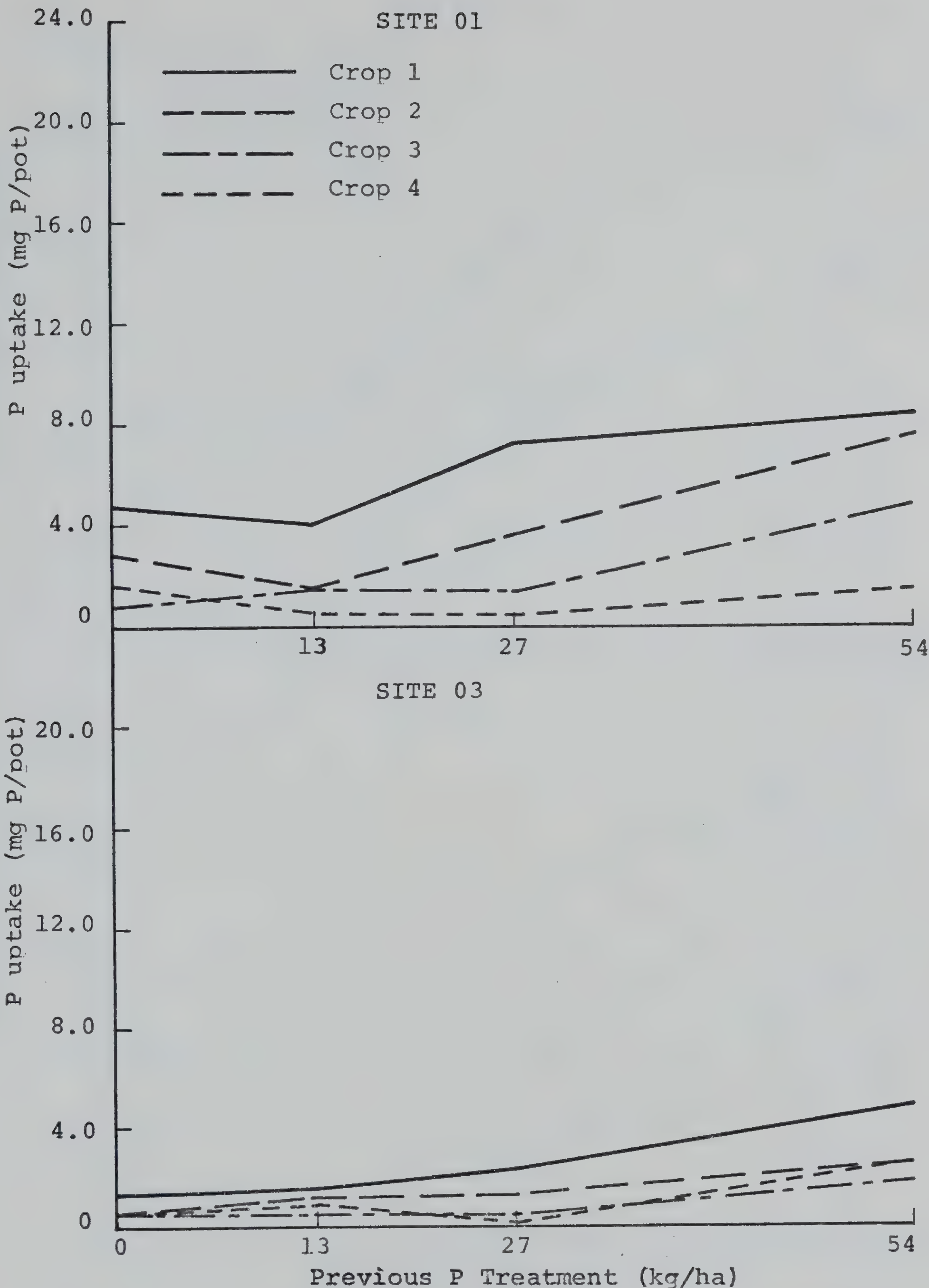


Figure 11 (top and bottom) Phosphorus uptake by barley plants in the greenhouse

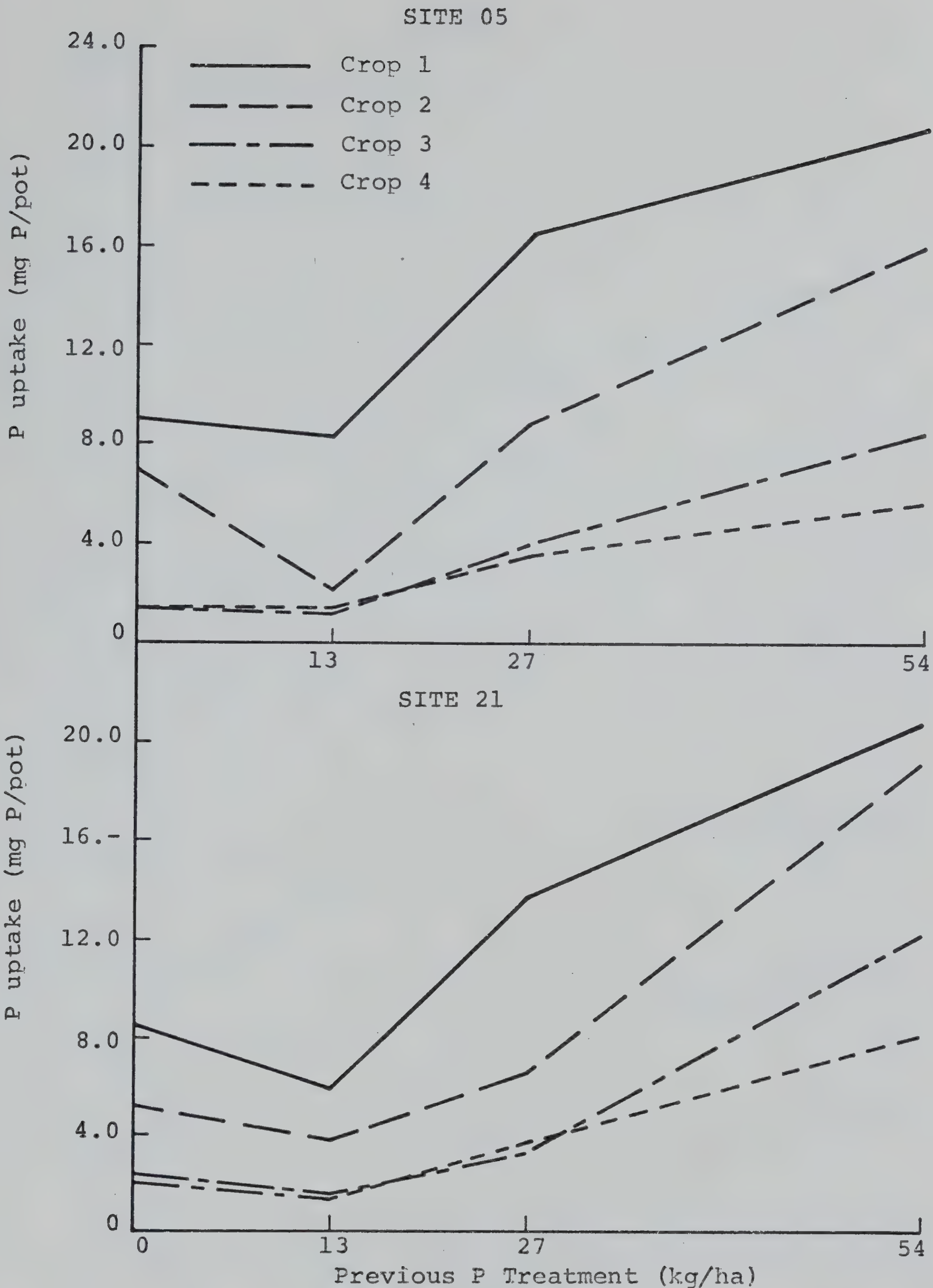


Figure 12 (top and bottom) Phosphorus uptake by barley plants in the greenhouse

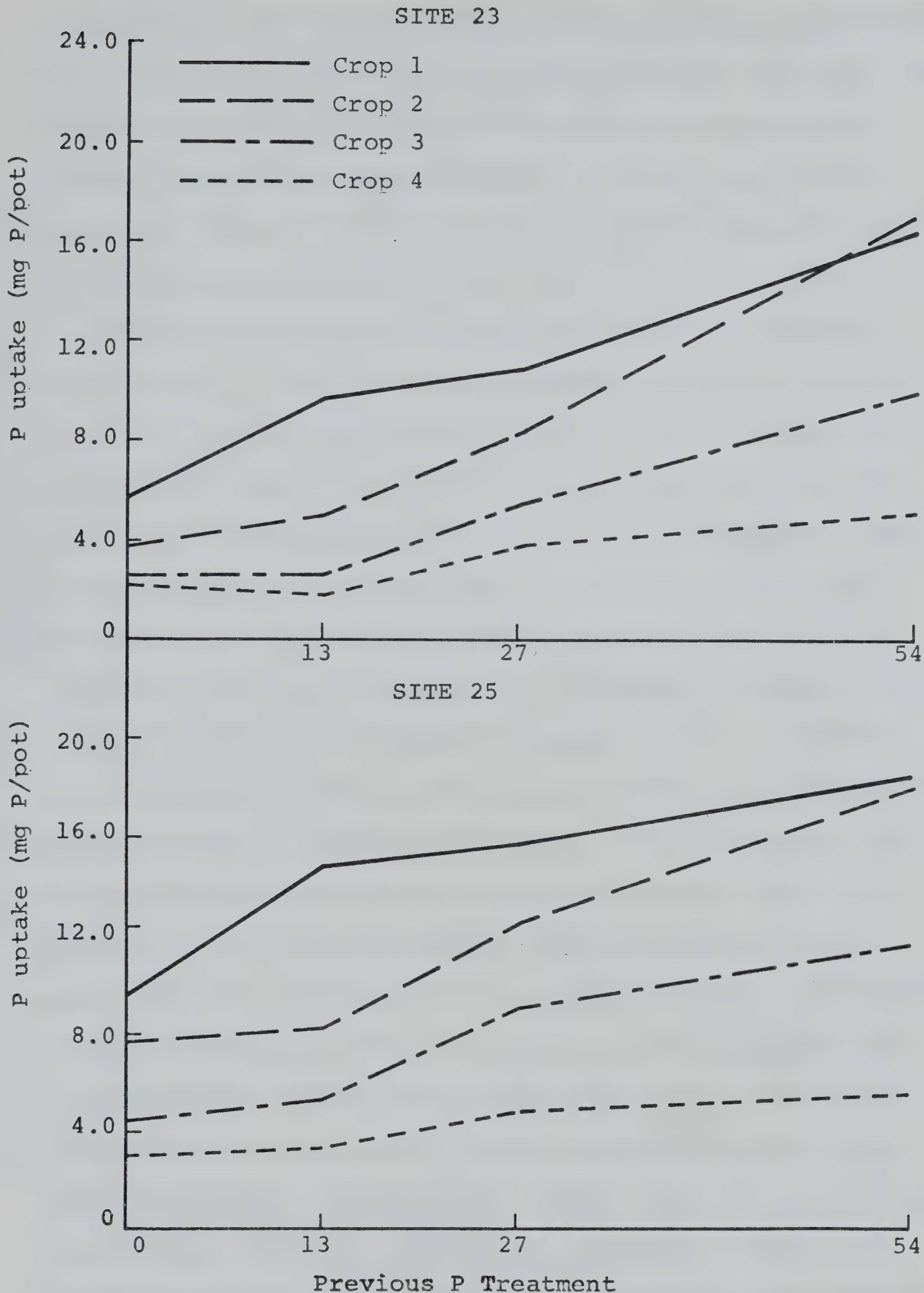


Figure 13 (top and bottom) Phosphorus uptake by barley plants in the greenhouse

ha than when it was 0 kg P/ha. These results are similar to the trends observed for yields (Figs. 5-7) and phosphorus content (Figs 8-10). As discussed previously, nitrogen was added in the field to the plots receiving the 13 kg/ha rate of phosphorus, which may have increased phosphorus uptake in the field and caused yield and phosphorus content reduction in the greenhouse.

For most sites there was a progressive decrease in phosphorus uptake which is evident for each of the previous phosphorus treatments from crop 1 through crop 4 indicating that not only can residual phosphorus be built up in the soil, but that it can also be utilized by plants. This trend was shown by the extractable phosphorus data (Fig. 1-3) the dry matter yield data (Figs. 5-7), the phosphorus content data (Figs. 8-10) and now the phosphorus uptake data (Figs. 11-13). Those sites which were originally low in extractable phosphorus (sites 01 and 03), showed a rapid decline in phosphorus uptake and by the fourth crop, little residual phosphorus was absorbed by the plants for any of the previous phosphorus treatments. This was supported by the fact that for both sites, severe phosphorus deficiency symptoms were noticeable on all previous phosphorus treatments before the fourth crop. For sites 05 and 21, which were originally medium in extractable phosphorus in the soil (medium by comparison of the six sites in this study), phosphorus uptake also decreased over the four crops but some differences in uptake among the previous phosphorus treatments were still noticeable by the fourth crop. For the lower previous phosphorus rates of these two sites, some phosphorus deficiency symptoms were noticeable but they were not as apparent as those for sites 01 and 03. For sites 23 and 25, which were originally high in extractable phos-

phorus in the soil, the decrease in phosphorus uptake over the four crops was progressive and well-defined. By the fourth crop deficiency symptoms were beginning to appear on the check pots, indicating that phosphorus uptake was marginal. For the remaining three previous phosphorus treatments however, the plants were very healthy, and the phosphorus uptake data suggested that they could still grow one or more crops before the plants would begin to show deficiency symptoms.

C. Field Data

N and P fertilizers were added from the commencement of the experiment (1964 or 1965) through the 1968 crop year. No fertilizers were added in 1969 through 1971. From 1971 - 1973 inclusive, blanket applications of nitrogen were applied to all plots but no phosphorus was applied. The yields for the specific plots from which the greenhouse samples were obtained are reported in Table 4.

The field yield data can be split into two separate time periods; the first being the years 1964 - 1968 in which phosphorus was added to the soil, and the second being the years 1969 - 1973 during which no phosphorus was added. For the first four or five years one might expect a progressive yield increase, at least for plots receiving lower P rates on soils initially low in extractable phosphorus. However, the results show no such trend, the yields varying for any given site with the yearly weather conditions.

For the years 1969 - 1973 it was expected that field yields might show trends similar to those exhibited in the greenhouse yields. In the greenhouse a progressive yield decrease was noted in most cases for each previous phosphorus treatment over the four greenhouse crops (Figs. 5-7 and Appendix A-7). However, no such trend was evident for

TABLE 4

Barley grain yields in the field.

Site	P. (kg/ha)	Yield (q/ha) 1964*	1965*	1966*	1967*	1968* +
01	0	12.4	23.5	16.4	12.8	13.4
	13	18.3	30.2	18.5	17.8	21.5
	27	22.8	29.5	30.4	24.1	24.5
	54	27.4	17.7	17.0	16.4	19.7
03	0		13.4		11.2	
	13	N/A	20.7	N/A	18.3	N/A
	27		11.8		12.9	
	54		15.7		15.8	
05	0		13.6	10.8	15.9	10.4
	13	N/A	24.5	18.4	21.4	13.7
	27		19.5	12.5	19.8	14.7
	54		15.2	11.2	14.9	7.3
21	0	19.0	13.0	35.1	17.8	13.3
	13	27.0	29.0	34.4	28.3	17.8
	27	25.1	23.5	25.8	23.9	16.3
	54	23.7	28.0	29.5	18.0	6.3
23	0		9.5	11.2	18.9	14.7
	13	N/A	17.6	14.0	29.8	20.7
	27		9.7	11.1	26.0	18.0
	54		7.7	9.9	20.5	15.9
25	0		16.1	16.4	21.3	20.4
	13	N/A	22.0	17.1	34.6	19.0
	27		11.9	8.2	12.7	17.7
	54		8.0	5.8	10.4	19.2

* P fertilizer added annually

\+ P fertilization terminated after 1968

Yield (q/ha)

1969	1970	1971	1972	1973
6.9	7.9		17.9	20.4
12.3	11.4	N/A	20.6	21.0
20.1	13.7		27.9	31.3
13.8	11.6		34.9	32.5
4.7			9.0	10.4
8.1	N/A	N/A	10.0	12.6
3.2			19.9	18.1
3.8			22.3	25.6
4.6	8.4		30.5	25.6
4.6	8.4	N/A	31.5	31.9
6.5	11.1		30.5	43.2
6.3	8.4		29.9	34.3
16.5	15.8		33.0	40.4
17.2	27.5	N/A	40.1	26.9
11.9	21.3		34.8	41.2
12.8	20.9		38.4	44.2
11.3	10.2	10.0		32.1
11.4	16.8	9.8	N/A	24.7
10.3	17.9	8.8		33.1
11.8	14.0	8.5		44.7
11.9	11.6	7.2	28.3	43.4
17.2	17.2	9.3	33.5	43.4
10.1	11.0	6.5	32.7	32.6
8.1	11.1	6.6	23.1	45.6

the field yields. One reason for this was that when the phosphorus applications were terminated in 1968, so too were the nitrogen applications. This may have resulted in the very poor yields which were evidenced from 1969 - 1971 inclusive. In 1972 and 1973 a blanket application of nitrogen was added to all sites. The 1972 and 1973 crops, as a result of this added nitrogen, showed excellent yields and good residual effects of the previously applied phosphorus. This is especially true for sites 01 and 03 which were originally low in extractable phosphorus. Sites 23 and 25, which were originally high in extractable phosphorus, showed little in the way of residual effects. To this author, it would appear that if nitrogen had not been a limiting factor from 1969 - 1971, yields in the field would likely have shown a similar trend to the yields for the greenhouse crops.

V GENERAL DISCUSSION

For the four or five years that fertilizer phosphorus was added to the six sites (13-54 kg P/ha/yr), totals ranging from 52-270 kg P/ha were applied. Percent phosphorus in the barley grain was not determined but an average value of 0.4% P (Martin et al 1972) would likely be applicable. Crop removals would therefore average approximately 7 kg P/ha/yr or approximately 42-49 kg P/ha by the time the soil samples were taken (6 - 7 years after commencing the field plots). This is an estimate only since not all crops were harvested (hence no phosphorus removal), and not all crops or treatments would contain 0.4% phosphorus. The plots with low levels of extractable phosphorus may have had 5-6 kg P/ha/yr for a total of 30-40 kg P/ha removed while plots with higher levels of phosphorus may have had 6-8 kg P/ha/yr for a total of 36-56 kg P/ha removed. Thus, the phosphorus removals by the field crops were somewhat smaller than additions. Hence, if there is no loss of phosphorus because of leaching or in gaseous forms (and no loss would be expected), there should be a net increase of 10-20 kg P/ha on some plots and up to 175-200 kg P/ha on others.

The total phosphorus results (Table 3) showed a general increase in soil phosphorus for each site from the 0 to 54 kg P/ha/yr rate, but little indication of phosphorus gain for the 3, 13 and 27 kg P/ha/yr rates. The precision of the total phosphorus method was not high and probably accounts for the lack of difference among the lower phosphorus rates. However, while the total phosphorus results did not show pronounced gain differences, they did give an estimate of the phosphorus status of the soil before the project began and also helped to show the relative "fixing" capacity of each of the soils when the total

phosphorus data were compared with the extractable phosphorus results (Appendix A-6). The three chernozemic sites (01, 05 and 21) showed similarly high total phosphorus in the soil but the extractable phosphorus levels for site 01 were somewhat lower than for sites 05 and 21, suggesting that the "fixing" capacity of the site 01 soil was somewhat greater. The three Luvisolic sites showed lower total phosphorus values (03 was lower than 23 and 25). The extractable phosphorus levels for site 03 were also very low but the levels for sites 23 and 25 were very high. It seems apparent that the soil of site 03 was originally low in phosphorus and also had a high "fixing" capacity. The site 23 and 25 soils were likely low also but have low "fixing" capacities and therefore show high extractable phosphorus increases after four or five years of phosphorus fertilization.

All sites showed some extractable phosphorus accumulation although not approaching the theoretical 175-200 kg/ha mentioned previously. The amount of the increase was dependent upon the original phosphorus in the soil, the rate of phosphorus applied and the "fixing" capacity of each soil.

After the phosphorus in the soil has been built up, are plants then able to utilize it? Extractable phosphorus (Figs. 1-3), dry matter yields (Figs. 5-7) and phosphorus uptake data (Figs. 11-13) all show decreases with cropping in the greenhouse. Good correlations exist between extractable phosphorus levels and yield, phosphorus content and phosphorus uptake (Table 5). It is apparent then that not only is extractable phosphorus built up in the soil over time; but this "residual" phosphorus can be utilized by plants. However, once the extractable phosphorus decreases to 5-10 ppm, crop yields are very low

TABLE 5

Linear correlation coefficients for extractable phosphorus vs. yield, phosphorus content and phosphorus uptake for the four greenhouse crops.

Variables	Ext P vs Yield	Ext P vs P content	Ext P vs P uptake
Crop No	"r" Values		
1	0.76	0.74	0.87
2	0.71	0.58	0.77
3	0.85	0.93	0.93
4	0.79	0.82	0.96

and pronounced deficiency symptoms are evident.

Farmers commonly add 6-13 kg P/ha (15-30 lb P_2O_5/ac), which is at the lower end of the range studied in this project. Thus, their additions may be little, if any, above the average crop removals (average removal of 7 kg P/ha/yr). Therefore, little increase in extractable phosphorus and hence little residual effects on crops would be expected. However, phosphorus levels would be maintained. Where higher rates of phosphorus are being added (e.g. 20-25 kg P/ha or 50 lb P_2O_5/ac), then one would expect a definite increase in extractable phosphorus levels over a number of years. Eventually it should be possible to reduce fertilizer applications without reducing yields. The higher rates would also give a definite residual phosphorus effect on plants which would be most evident on low phosphorus soils. This is shown by the greenhouse data (Figs. 1, 5, 8 and 11) and the field data (Table 4) for sites 01 and 03.

What is the practicality of this study? The average farmer is not likely to add more phosphorus than needed in the current year just to build up the soil phosphorus. It is more likely that he will add enough phosphorus to maximize returns in the current year and take whatever residual effect he gets as a "fringe benefit". Tc get maximum returns the farmer will likely have to add much more phosphorus than the crop is likely to use, especially on soils low in phosphorus (the majority of soils). Eventually, then, one should expect extractable phosphorus to increase, thereby reducing the current phosphorus requirements.

Heapy (submitted) showed that the current optimum phosphorus rate was given by the equation:

$$P_A{}^1 = 19.6 - 0.23\ P_S$$

where $P_A{}^1$ = economic optimum phosphorus rate to add in kg/ha, and P_S = extractable phosphorus in kg/ha. This equation can be applied to two "extreme" field situations. First, if P_S is 10 kg/ha (approx. 5 ppm), then:

$$\begin{aligned} P_A{}^1 &= 19.6 - (0.23)(10) \\ &= 17.3 \text{ kg/ha} \end{aligned}$$

Thus, based on this data, one would recommend that on the lowest testing soils (sites 01 and 03), farmers might apply about 17 kg P/ha. This rate would be between the 13 and 27 kg P/ha rates used in this study. After a few years the extractable phosphorus would be increased to 20 kg/ha for example. At this time one could then reduce $P_A{}^1$ as follows:

$$\begin{aligned} P_A{}^1 &= 19.6 - (0.23)(20) \\ &= 15 \text{ kg P/ha} \end{aligned}$$

Secondly, if P_S is 50 kg/ha (=25 ppm), then:

$$\begin{aligned} P_A{}^1 &= 19.6 - (0.23)(50) \\ &= \ \ 8.1 \text{ kg/ha} \end{aligned}$$

This rate is below the lowest (13 kg P/ha) rate used in the present study and there would therefore be no residual effect, i.e. no buildup of extractable phosphorus. This rate would in fact replace about the amount of phosphorus removed each year. These results appear to support Soper (1967), that on high phosphorus soils one should annually add 6-7 kg of phosphorus while on very low phosphorus soils one should add about 22 kg P/ha.

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APPENDIX

Appendix A-1. Determination of Total Phosphorus

Weigh 1 g of oven dried soil into a porcelain crucible and ignite in a muffle furnace at 600^{o}C for one hour. Transfer the ignited sample to a 100-ml teflon beaker with 1+1 HCl. Evaporate to about 10 ml. Add 15 to 20 ml conc. HCl to the beaker and evaporate to dryness. Add 10 ml of conc. HNO_3 and 10 ml of 48% HF to the beaker and again evaporate to dryness. This step is repeated. Dissolve the residue with 10 ml conc. HCl and 30 ml water. Transfer the solution to a 200-ml volumetric flask. To the beaker add a few ml of 1+1 HCl and place back on the sand bath to remove the residue. Transfer the solution to the same flask and make solution up to volume with 5% HCl. A blank extract is prepared in the same way with all the reagents except soil. Phosphorus in the extract is determined by the ascorbic acid-reduced molybdophosphoric blue color method in H_2SO_4 system as described in Appendix A-2.

Appendix A-2. Ascorbic Acid-Reduced Molybdophosphoric Blue Color Method in H_2SO_4 System.

a) Reagents

Reagent A-- Dissolve 12 g of ammonium molybdate in 250 ml of water. In 100 ml of water dissolve 0.2908 g of antimony potassium tartrate. Add both of the dissolved reagents to 1 liter of 5N H_2SO_4, mix thoroughly and make to 2 liters. Store in pyrex glass bottle in a dark and cool compartment.

Reagent B-- Dissolve 1.056 g of ascorbic acid in 200 ml of reagent A. Prepare this reagent as required as it does not keep for more than 24 hours.

b) Determination of Phosphorus

Pipette aliquots containing 1 to 20 ug (0.08 to 0.80 ppm P in final volume) of orthophosphate into 25 ml-volumetric flasks. Adjust to pH 5 using p-nitrophenol indicator. Predetermine the amount of acid or alkali needed to bring pH to 5 in some aliquots and dispense the same amount to all unknowns. Add water to 20 ml and then add 4 ml of reagent B and the solution is made to volume. The color is stable for 24 hours and maximum intensity is obtained in 10 min. Read the color intensity on a spectrophotometer at 882 mu.

Appendix A-3. Wet Digestion Procedure for the Analysis of Plant Material.

Grind the dry matter to pass through a 20-mesh screen. Weigh 0.500 g of this into a 100-ml test tube. Add 12 ml of conc. HNO_3, then 2 ml of conc. $HClO_4$. Predigest at room temperature for 1 hour; digest at higher temperature for 1 to 2 hours. Dilute the clear extract to 200 ml, then take a 2 or 5 ml aliquot for phosphorus determination. Phosphorus in the extract is determined by the ascorbic acid-reduced molybdophosphoric blue color method in H_2SO_4 system as described in Appendix A-2.

APPENDIX A-4

pH of soils used in greenhouse experiments.

Previous P (kg/ha)	01	03	05	21	23	25
0	6.1	6.4	6.9	5.8	6.5	6.2
13	6.0	5.6	6.6	6.0	6.3	6.3
27	6.1	6.2	6.6	6.0	6.3	6.4
54	5.9	6.2	6.7	6.1	6.4	6.4

APPENDIX A-5

Extractable phosphorus on the soils prior to, and after each greenhouse experiment.

Site	Previous P (kg/ha)	Extractable P (ppm) after crop numbers: 0*	1	2	3	4
01	0	8.7	4.1	4.0	2.5	2.5
	13	8.4	5.6	5.0	4.5	2.5
	27	18.0	7.2	7.0	5.0	3.7
	54	31.2	17.5	14.0	10.5	7.5
03	0	9.0	6.9	4.5	4.0	2.5
	13	8.7	5.6	5.5	5.0	2.5
	27	11.0	6.9	5.0	6.0	3.7
	54	31.5	19.1	17.0	16.0	11.2
05	0	20.5	8.7	4.4	6.2	3.7
	13	17.0	8.1	6.2	6.2	3.7
	27	52.0	25.0	16.2	12.5	10.0
	54	61.2	43.7	31.2	26.2	20.0
21	0	31.2	10.0	10.0	8.7	8.7
	13	55.6	15.0	6.2	6.2	3.7
	27	47.5	30.0	21.2	15.0	12.5
	54	91.0	16.2	53.7	47.5	38.7
23	0	30.0	21.2	17.5	15.0	12.5
	13	37.5	28.7	22.0	17.5	16.2
	27	55.0	41.2	31.2	23.7	21.2
	54	83.7	58.7	47.5	36.2	31.2
25	0	48.7	27.5	21.2	16.2	15.0
	13	50.0	32.5	38.0	20.0	17.5
	27	73.7	50.5	33.7	26.2	21.2
	54	93.1	61.2	50.0	40.0	32.5

* 0 - prior to crop #1

APPENDIX A-6

Extractable phosphorus by 2 methods on the soil samples prior to first greenhouse experiment.

Site	Previous P (kg/ha)	Extractable Phosphorus (ppm)	
		Olsen Method	Miller & Axley Method
01	0	8.2	8.7
	13	9.0	8.4
	27	16.0	18.0
	54	25.5	31.2
03	0	9.7	9.0
	13	9.2	8.7
	27	12.0	11.0
	54	21.0	31.5
05	0	14.7	20.5
	13	12.7	17.0
	27	34.3	52.0
	54	46.1	61.2
21	0	18.0	31.2
	13	12.0	55.6
	27	30.2	47.5
	54	58.5	91.0
23	0	19.0	30.0
	13	16.5	37.5
	27	30.2	55.0
	54	41.0	83.7
25	0	26.5	48.7
	13	29.0	50.0
	27	36.0	73.7
	54	48.0	93.1

APPENDIX A-7

Dry matter yield for the four greenhouse experiments.

Site	Prev. P (kg/ha)	Dry matter yield (g) for crop numbers: 1		2		3		4		Total
		a*	b+	a	b	a	b	a	b	b+
01	0	3.52	1.90	6.02	1.60	3.94	0.56	2.33	1.05	5.11
	13	3.56	1.64	5.60	1.01	4.32	0.99	3.15	0.48	4.12
	27	4.44	3.50	5.87	2.05	4.59	1.04	2.88	0.45	7.04
	54	4.35	3.62	5.49	4.32	4.32	2.72	3.32	1.09	11.75
03	0	3.11	0.78	5.09	0.66	3.15	0.55	2.42	0.51	2.50
	13	3.70	0.90	4.50	0.81	3.48	0.40	1.97	0.53	2.64
	27	3.70	1.30	5.13	1.00	3.22	0.47	2.54	0.31	3.08
	54	3.05	1.95	5.08	1.85	2.93	1.28	2.51	1.61	6.69
05	0	4.07	3.47	4.52	3.81	3.87	1.02	3.48	1.06	9.36
	13	3.56	3.24	6.58	1.85	4.26	0.91	3.10	1.25	7.25
	27	4.14	3.97	5.99	6.02	4.60	2.40	3.26	2.80	15.19
	54	4.29	4.06	6.88	6.73	4.67	3.79	3.10	2.81	17.39
21	0	4.93	4.05	5.88	5.26	4.26	1.88	3.35	1.83	13.02
	13	5.03	4.00	7.08	4.24	5.18	1.49	3.39	1.59	11.32
	27	4.84	4.20	6.89	4.21	4.57	4.16	3.92	2.58	15.15
	54	4.44	4.30	6.15	6.24	4.67	4.27	3.43	3.47	18.28
23	0	3.95	3.20	7.78	4.13	3.99	1.75	3.20	2.12	11.20
	13	4.33	3.94	5.64	5.09	3.00	1.89	2.77	1.60	12.52
	27	4.04	3.77	5.91	5.24	4.12	2.76	2.66	2.53	14.30
	54	4.48	4.05	4.09	5.37	4.24	3.73	2.75	2.37	15.52
25	0	4.55	4.20	5.80	5.15	3.61	2.83	3.22	2.41	14.59
	13	4.40	4.35	5.71	5.18	4.31	2.84	3.08	2.62	14.99
	27	4.43	3.95	5.81	5.43	4.27	3.98	2.73	2.42	15.78
	54	4.47	4.66	6.00	6.00	4.70	4.36	2.93	3.32	18.35

* a - yield of pots fertilized in greenhouse

\+ b - yield of pots not fertilized in greenhouse

APPENDIX A-10

Phosphorus content in the plant material (tops) for the four greenhouse crops.

Site	Prev. P (kg/ha)	Phosphorus content (%) in crop numbers: 1		2		3		4		Average	
		a*	b+	a	b	a	b	a	b	a	b
01	0		0.25		0.18		0.15		0.18		0.19
	13		0.25		0.16		0.16		0.15		0.18
	27		0.21		0.19		0.15		0.14		0.17
	54	0.34	0.24	0.30	0.18	0.29	0.17	0.36	0.17	0.32	0.19
03	0		0.19		0.10		0.10		0.14		0.13
	13		0.18		0.15		0.13		0.19		0.16
	27		0.19		0.14		0.12		0.14		0.15
	54	0.27	0.26	0.20	0.15	0.25	0.16	0.23	0.18	0.24	0.19
05	0		0.26		0.19		0.14		0.15		0.18
	13		0.26		0.12		0.13		0.16		0.17
	27		0.42		0.15		0.17		0.15		0.22
	54	0.51	0.52	0.35	0.24	0.37	0.23	0.41	0.24	0.41	0.31
21	0		0.21		0.10		0.13		0.13		0.18
	13		0.15		0.09		0.11		0.13		0.17
	27		0.33		0.16		0.18		0.17		0.22
	54	0.53	0.49	0.40	0.31	0.38	0.29	0.32	0.28	0.41	0.31
23	0		0.18		0.09		0.15		0.12		0.14
	13		0.25		0.10		0.14		0.14		0.12
	27		0.29		0.16		0.20		0.17		0.21
	54	0.48	0.41	0.35	0.32	0.34	0.27	0.40	0.25	0.39	0.34
25	0		0.23		0.15		0.16		0.15		0.17
	13		0.34		0.16		0.19		0.15		0.21
	27		0.40		0.23		0.23		0.23		0.27
	54	0.52	0.40	0.40	0.30	0.35	0.27	0.40	0.27	0.42	0.31

* a - P content of pots fertilized in greenhouse

\+ b - P content of pots not fertilized in greenhouse

APPENDIX A-9

Phosphorus uptake by barley plants in four greenhouse experiments.

Site	Previous P (kg/ha)	Phosphorus uptake (mg) for crop numbers:			
		1	2	3	4
01	0	4.75	2.88	0.84	1.89
	13	4.10	1.62	1.58	0.72
	27	7.35	3.69	1.56	2.63
	54	8.69	7.78	4.90	1.85
03	0	1.48	0.66	0.58	0.71
	13	1.62	1.21	0.52	1.00
	27	2.47	1.40	0.56	0.43
	54	5.07	2.77	2.05	2.90
05	0	9.02	7.24	1.43	1.59
	13	8.42	2.22	1.27	2.00
	27	16.67	9.03	4.08	4.20
	54	21.11	16.15	8.72	6.74
21	0	8.50	5.26	2.44	2.38
	13	6.00	3.82	1.64	2.07
	27	13.86	6.74	7.51	4.39
	54	21.07	19.34	12.40	9.71
23	0	5.76	3.72	2.62	2.54
	13	9.85	5.09	2.65	2.24
	27	10.93	8.38	5.52	4.30
	54	16.60	17.18	10.07	8.42
25	0	9.66	7.72	4.53	3.61
	13	14.80	8.29	5.40	3.93
	27	15.80	12.49	9.15	5.56
	54	18.64	18.00	11.77	8.96

APPENDIX A-10

Analysis of variance of the dry matter yield data for the four greenhouse crops.

Crop	Site	Previous P (kg/ha)	S X P
	"F" Values		
1	68.0*	8.7*	0.9
2	98.6*	36.5*	5.0*
3	47.0*	51.9*	3.1*
4	109.0*	46.0*	9.6*

* Significant at the 1% level